RELATIVE SEA LEVEL CONTROL OF INCISED SHOREFACE SEDIMENTS IN THE BURNSTICK MEMBER, CARDIUM FORMATION, UPPER CRETACEOUS, ALBERTA.

RELATIVE SEA LEVEL CONTROL OF INCISED SHOREFACE SEDIMENTS IN THE BURNSTICK MEMBER, CARDIUM FORMATION, UPPER CRETACEOUS, ALBERTA.

By

SIMON ALAN JAMES PATTISON, B.Sc.

A Thesis
Submitted to the School of Graduate Studies
in Partial Fulfilment of the Requirements
for the Degree
Master of Science

McMaster University

1987

Master of Science (Geology)

McMaster University Hamilton, Ontario

Title: Relative Sea Level Control of Incised Shoreface Sediments in the Burnstick Member, Cardium Formation, Upper Cretaceous, Alberta.

Author: Simon Alan James Pattison, B.Sc.(Specialist) (Brandon University)

Supervisor: Dr. R.G. Walker

Number of Pages: xvi, 206.

ABSTRACT

The Burnstick Member of the Cardium Formation (Turonian, Upper Cretaceous) occurs in the subsurface of southern Alberta and is underlain by the Hornbeck Member and overlain by the Raven River Member. These sediments were deposited into the Alberta Foreland Basin along the eastern margin of the Canadian Cordillera.

The Burnstick Member sediments appear to be tens of kilometers east of the closest known paleoshoreline (Kakwa Member, Cardium Formation) which presents a major problem with respect to sediment transport in an offshore environment. Two possibilities exist for the deposition of the Burnstick Member sediments including, direct emplacement into an offshore environment by storm related currents ("offshore bars") or deposition in a shoreface environment during a rapid lowering of sea level (incised shoreface deposits).

Approximately 200 cores and 800 geophysical well logs were used to determine the sedimentology and sand body geometry of the oil and gas fields at Caroline, Crossfield, Garrington and Lochend.

Well log cross sections, core cross sections and isopach maps show that the Burnstick Member rests on a major erosional surface (E4) that outlines a "one-sided scour" or "bevel" which is open towards the northeast. The scours are between 2 - 6 m deep and are interpreted to have developed in shoreface environments.

In between the fields the E4 surface merges with the T4 surface (Burnstick - Raven River Member contact) and forms the E4/T4 surface. The E4/T4 surface is flat relative to a horizontal lower marker and combined with the incised E4 surface underneath the four fields defines a step-like topography across the study area.

Ten facies are combined into two vertical facies sequences; a coarsening upwards Burnstick Member sequence and a fining upwards lower Raven River Member sequence. Both facies sequences are best developed in the on-field positions, where they reach a maximum thickness of 7 meters. In contrast, the off-field development of the two facies sequences is poor and rarely exceeds 0.25 meters.

The Burnstick Member sediments are concentrated in three long, linear and narrow belts in the study area and rest within the incised, one-sided scours of the E4 surface. The belts are approximately 15 km apart, oriented NW-SE and are traceable throughout the study area.

The problem of transporting and focussing sediments in an offshore environment does not apply to the Burnstick Member sediments as they are interpreted to be incised shoreface deposits that were localized on the Cretaceous shelf during sea level fluctuations. Four sea level changes are hypothesized including one large lowering to move the shoreface from west of the study area to a position at Garrington, and three small rises to move the shoreface from Garrington to Caroline/Crossfield, from Caroline/Crossfield to Lochend, and from Lochend to west of the study area. Indirect evidence suggests that fluvial channels cut across the exposed shelf and supplied sediments to the incised shorefaces.

ACKNOWLEDGEMENTS

First and foremost, I wish to thank Roger Walker for his excellent supervision of my M.Sc. thesis. I appreciate his endless enthusiasm, critical thought and insight shown towards my work. Roger has most importantly taught me to critically analyze scientific ideas through his courses and supervision of this thesis.

I would also like to thank the Natural Science and Engineering Research Council of Canada for awarding operating and strategic grants to Roger Walker, and for also awarding the author with a Post Graduate Scholarship (PGS2). The awarding of the Harry Lyman Hooker Scholarship (McMaster University) and the Christopher Riley Memorial Graduate Scholarship (Brandon University) to the author are also appreciated.

The efficient and helpful staff at the Alberta Energy Resources Conservation Board, Core Research Center in Calgary made the collection of the core data an easy process. To them I extend my thanks. The logistical support of Home Oil Co. Ltd., Calgary, for the collection of base maps and well logs is greatly appreciated. The author is indebted to Randy Hughes for providing me with great access to the data at Home Oil Co. Ltd. and for showing enthusiasm and interest towards my thesis. I wish to thank Jack Whorwood (McMaster University) for developing the photographs and for providing advice on the presentation of figures in a thesis. His friendly and patient nature is greatly appreciated. And last, but not least, I wish to thank Liz Barr and Mark Birchard for helping with the data collection in Calgary during the summer of 1986, and Felix Lee for drafting some of the thesis figures.

Many people have made my stay at McMaster University an enjoyable experience. Most of all, the friendship of Bruce Power, Dave McLean, Steve Prevec and Bill Buhay have provided the most memorable moments. I have also enjoyed the times with Shelley Leggitt, Janok Bhattacharya, Jeremy Bartlett and Tim Hart. Also, thanks to the staff at Tim Horton Donuts for making the best damn coffee **IN THE WORLD!!!**

On a more serious note I wish to mention the people that mean the most to me in my life. To Gillian, Alan, Andrew, Philip, and Elizabeth, your love and support is appreciated.

Table of Contents

Page

Page

Page

Page

List of Figures

Page

Page

CHAPTER 1: Introduction

1.1 Geological Problem

This thesis involves the study of the Burnstick Member of the Cardium Formation, in the subsurface of southern Alberta. The original scientific problem to be tackled in this thesis was to determine how the Burnstick Member sediments were transported and focussed into long and narrow sandbodies that appear to be tens of kilometers east of the closest paleoshoreline. These Burnstick Member sandbodies more or less coincide with producing oil and gas fields and are up to 100 km long, and 2 - 6 km wide. Marine mudstones encase the fields on all sides suggesting that the Burnstick Member sediments were deposited below wave base, in relatively deep water.

Transporting coarse grained sediments tens of kilometers offshore is problematic but not unreasonable. Various currents created during storm conditions could have the ability to transport sediments onto the shelf, and include, storm surge currents, density currents and turbidity currents. However, focussing the deposits of such currents into long and narrow "ridges" or "offshore bars" is a more difficult problem. A theoretical model has been proposed by Swift and Rice (1984) to explain the focussing of coarse sediments in a shelf environment. This model is based on the deceleration of a sediment-water current over a topographic high leading to the deposition of the sediments. Some of the problems left unsolved by this model are; (1) the development of a long and narrow topographic high on the shelf, (2) the consistent focussing of sediments over the topographic high during the deposition of the "offshore bar" and, (3) the abrupt termination of the sediment supply or the destruction of the topographic high after the "offshore bar" is deposited. These problems, coupled with the lack of a documented modern example of this process leaves this model in the theoretical stage.

Work by Plint et al. (1986) in the Cardium Formation of southern Alberta has led to the redefinition of the origin of "offshore bars". The recognition of seven basin wide erosional surfaces in the Cardium Formation, labelled E1 through to E7, suggests that sea level fluctuations play an important role in localizing sediments on the Cretaceous shelf. It is believed that each erosional surface developed during a lowering of sea level in the Western Interior Seaway, resulting in the deposition of shoreface sediments in an area that was previously under tens of meters of water. A transgression follows each regressive event, burying the shoreface sediments with marine mudstones. Bergman (1987), Bergman and Walker (1987), Leggitt (1987) and McLean (1987) use this hypothesis to explain the deposition of the conglomeratic Carrot Creek Member on top of the E5 surface in the Carrot Creek, Pembina and Ferrier fields. This hypothesis will be tested on the E4 surface that rests stratigraphically below the E5 surface.

The purpose of this thesis is to determine if the Burnstick Member sediments are "offshore bars" or incised shoreface deposits. This will be accomplished by studying the sedimentology and sand body geometry of the Burnstick Member in south - central Alberta. The geometry of the lower contact (E4 surface) will be of particular importance as it will indicate if the Burnstick Member is "offshore bar-like" (convex up E4 surface) or "shoreface - like" (sigmoidal E4 surface).

The area chosen for this study provides an excellent oppurtunity for solving this problem. Four long and narrow Burnstick Member fields are observed in the study area, namely Caroline, Crossfield, Garrington and Lochend. Data from these four fields will provide the basis for this thesis.

1.2 Previous Work

The purpose of this section will be to briefly discuss the development of ideas concerning the depositional environment of the Cardium Formation. Both outcrop and subsurface studies have contributed to the present understanding of the Cardium Formation. The latter part of this section will focus on the previous studies of the Burnstick Member. For a more complete review of the history of ideas surrounding the Cardium Formation the reader is referred to Stott (1963) and Walker (1983a).

Cardium Formation

Four main stages can be identified in the evolution of ideas concerning the depositional environment of the Cardium Formation. These can be simplified into the following categories, (1) turbidity current deposits (Beach, 1955), (2) shallow marine deposits (DeWiel, 1956; Michaelis, 1957; Nielsen, 1957; Stott, 1963), (3) storm dominated turbidity current deposits (Michaelis and Dixon, 1969; Swagor et al., 1976; Wright and Walker, 1981; Walker, 1983a; Krause and Nelson, 1984; Walker, 1985), and (4) incised shoreface deposits (Plint et al., 1986; Bergman and Walker, 1987; Bartlett, 1987; Bergman, 1987; Leggitt, 1987; McLean, 1987). In turn each one of these evolutionary stages will be discussed in order to highlight the observations used to develop these interpretations.

Beach (1955) proposed that the Cardium Formation was a turbidity current deposit based on the uniformity and continuity of the pebble horizons in the Cardium Formation (Walker, 1983a). This interpretation received widespread criticism and was passed off as a sedimentological fashion (DeWiel, 1956). It is interesting to note that the ideas of Beach (1955) resurfaced again in the early 1980's.

The second evolutionary stage in the interpretation of the Cardium Formation occured initially as a rebuttal to the controversial turbidity current interpretation proposed by Beach (1955). Various papers were written in the late 1950's that interpreted the Cardium Formation as a shallow marine deposit (DeWiel, 1956; Michaelis, 1957; Nielsen, 1957; MacDonald, 1957). These interpretations were based on the sedimentary structures and sand body geometry of the Cardium Formation and include barrier island to deltaic interpretations (Walker, 1983a). By the early 1960's the shallow water "origin" of the Cardium Formation was firmly entrenched in the literature and was supported by the classic outcrop work of Stott (1963). Stott developed the first stratigraphic division of the Cardium Formation in outcrop and interpreted the Cardium Formation as the deposits of shallow water to transitional environments such as shorelines, beaches and barriers (Walker, 1983a).

The third evolutionary stage rekindled the ideas of Beach (1955) in suggesting that the Cardium Formation conglomerates were deposited tens of kilometers offshore by turbidity currents. Michaelis and Dixon (1969) first suggested the possibility of storm transport and deposition for the Cardium Formation facies in Pembina. A later paper by Swagor et al. (1976) suggested that the Carrot Creek conglomerates were transported and deposited by storm generated currents. Various papers followed which proposed the idea of storm generated turbidity currents as the most likely transporting and depositing mechanism for various Cardium sediments (Wright and Walker, 1981; Walker, 1983c; Krause and Nelson, 1984; Walker, 1985).

The fourth stage in the evolution of ideas on the Cardium Formation suggests that the Cardium Formation sandstones and conglomerates are incised shoreface deposits. This interpretation is based on the recognition of seven basin wide erosional surfaces in the subsurface of the Cardium Formation that can be correlated with the erosional surfaces in outcrop (Duke, 1985; Plint et al., 1986; Walker, 1986). The main Cardium sandstones and conglomerates rest within the incised parts of the erosional surfaces and have been interpreted to be incised shoreface deposits (Bergman and Walker, 1987; Bartlett, 1987; Bergman, 1987; Leggitt, 1987; McLean, 1987). This hypothesis, along with the hypothesis of depositing the Burnstick Member as "offshore bars" will both be examined in this thesis.

Burnstick Member

Two main Cardium Formation sandstones and conglomerates are identified in the subsurface of southern Alberta. These include the upper Cardium sandstone ("A" sand or Raven River Member) and the lower Cardium sandstone ("B" sand or Burnstick Member). Most of the work on the Cardium Formation has been concentrated on the upper Cardium sandstone and only a few studies have been completed on the lower Cardium sandstones (Berven, 1966; Walker, 1983b; Walker, 1983c; Plint et al., 1986).

Until recently, the only study of the lower Cardium sandstone was one by Berven (1966) that focussed on the sedimentology and sand body geometry of the lower sandstone in the Garrington -- Crossfield area. Berven (1966) concluded that the Cardium "B" sandstone was deposited tens of kilometers east of the closest paleoshoreline in an offshore environment. No transporting and depositing mechanism for the sediments in "offshore bars" was suggested by Berven (1966).

Seventeen years later, two papers by Walker (1983b, 1983c) discussed the regional stratigraphy and facies, and proposed formal names for Cardium Members. In the first paper, Walker (1983b) correlates the lower Cardium sandstone in the Garrington and Caroline fields based on their stratigraphic positions, gamma ray log response and the occurrence of a massive dark mudstone (black blanket) facies above the lower Cardium sandstones in each field. In the second paper, Walker (1983c) formally defines the lower Cardium sandstone as the Burnstick Member and identifies a consistent vertical facies sequence within the Burnstick Member of the Caroline to Garrington area. Walker (1983c) concluded that the Burnstick Member sediments in southern Caroline and Garrington were deposited at least 100 kilometers offshore and that the most probable transporting mechanism was turbidity currents.

Plint et al. (1986) redefined the classic Cardium problem of transporting and focussing coarse sediments in an offshore environment by identifying seven basin wide erosional surfaces in the Cardium Formation. One of these erosional surfaces, E4, underlies the Burnstick Member. Preliminary observations by Walker (1986) and Plint et al. (1986) suggest that the Burnstick Member sediments were deposited as lowstand conglomerates during a lowering of the sea level. This hypothesis, along with the "offshore bar" hypothesis will be examined in this thesis.

CHAPTER 2: Regional Setting and Stratigraphy

2.1 Introduction

The purpose of this chapter is to discuss the regional setting and stratigraphy of the Burnstick Member in relation to the Cardium Formation. This will be accomplished by discussing the age, areal extent, stratigraphy, structure, paleoclimate and paleogeography of the Cardium Formation in general. Where appropriate, it will be important to emphasize the relationship of the Burnstick Member to the Cardium Formation in these sections. This chapter will conclude with a description of the study area and the data base used in this thesis.

2.2 Age and Areal Extent

The Cardium Formation is Turonian (Upper Cretaceous) in age which has an absolute time span of 91 to 88.5 million years (Decade of North American Geology, Palmer, 1983). The Cardium Formation occupies the upper part of the Turonian and is believed to have been deposited in approximately 1 million years (Walker, 1986).

The Cardium Formation occurs over a wide area of Alberta and can be observed in outcrop and in the subsurface. Most of the outcrops of the Cardium Formation are located in the Foothills Deformed Belt between the Alberta -- Montana border and Dawson Creek, B.C. (Walker, 1986). This covers an area of approximately 700 km by 100 km. The subsurface occurrence of the Cardium Formation is also very extensive as numerous Cardium fields are observed from T25 up to T65 (Figure 2.1). The largest Cardium field is Pembina, which covers an area of approximately 2300 km^2 and represents the largest single oil field in western Canada and one of the largest stratigraphic traps in the world (Nielsen and Porter, 1984).

There are six different Cardium fields in the subsurface that produce oil and gas from the Burnstick Member, namely Caroline, Crossfield, Edson, Garrington, Lochend and Pine Creek (Figure 2.1). These six fields are observed over a wide area from T24/R1W5 (Crossfield) up to T55/R18W5 (Pine Creek).

2.3 Stratigraphy

The Cardium Formation consists of a coarse clastic wedge of sediments that was deposited into the Alberta Foreland Basin from the rising Canadian Cordillera. It is sandwiched in between the marine mudstones of the Wapiabi Formation (above) and the Blackstone Formation (below), and is approximately 100 meters thick in the subsurface (Figure 2.2). Together, these three formations constitute the Alberta Group, which is time equivalent to the Colorado Group in the United States (Stott, 1963).

Figure 2.1. The location of the Cardium oil fields in southwestern Alberta. Note the location of Caroline, Crossfield, Garrington and Lochend fields in relation to the other Cardium oil fields. Also note the limit of progradation of the Kakwa Member which is informally termed the Kakwa shoreface.

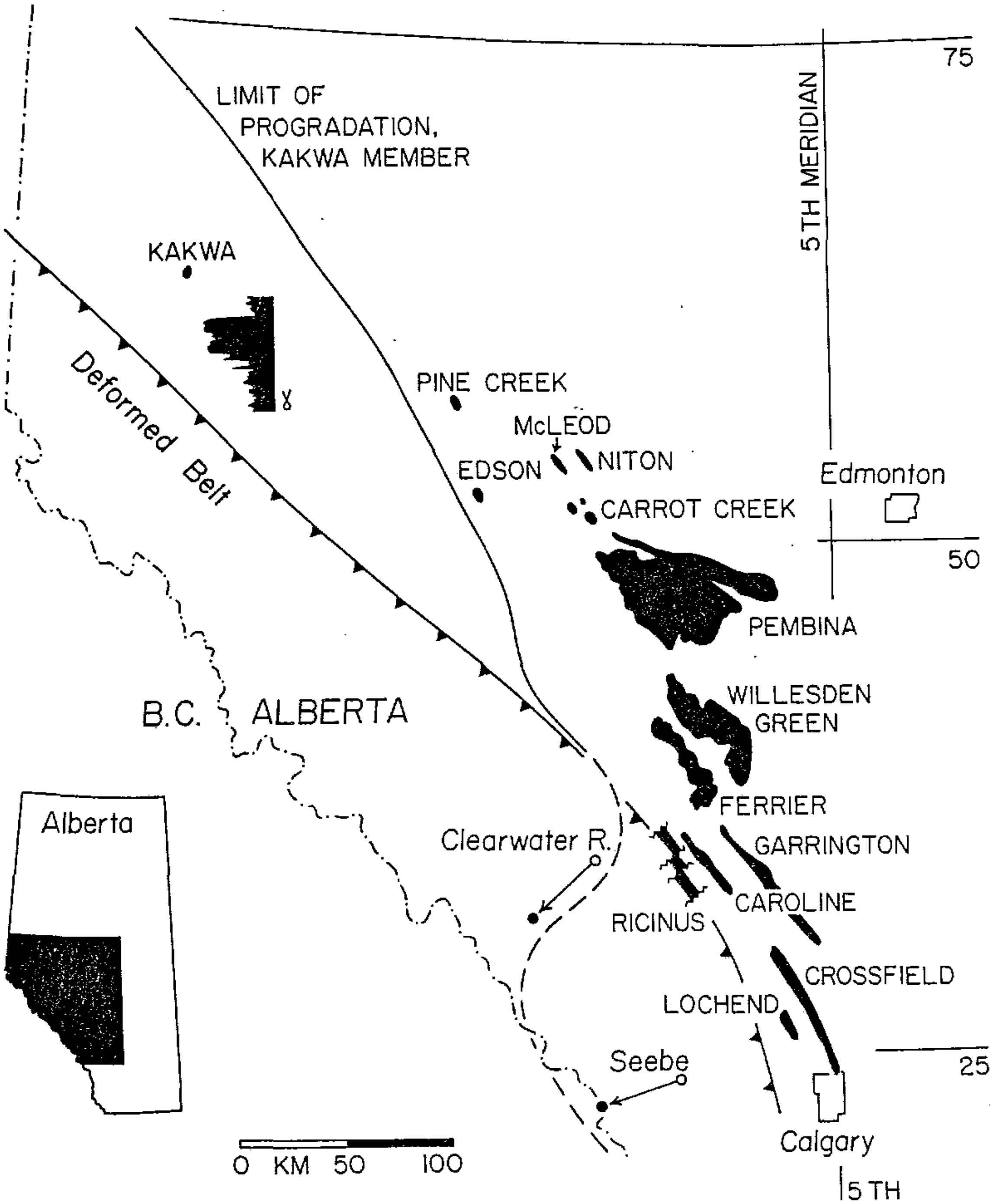
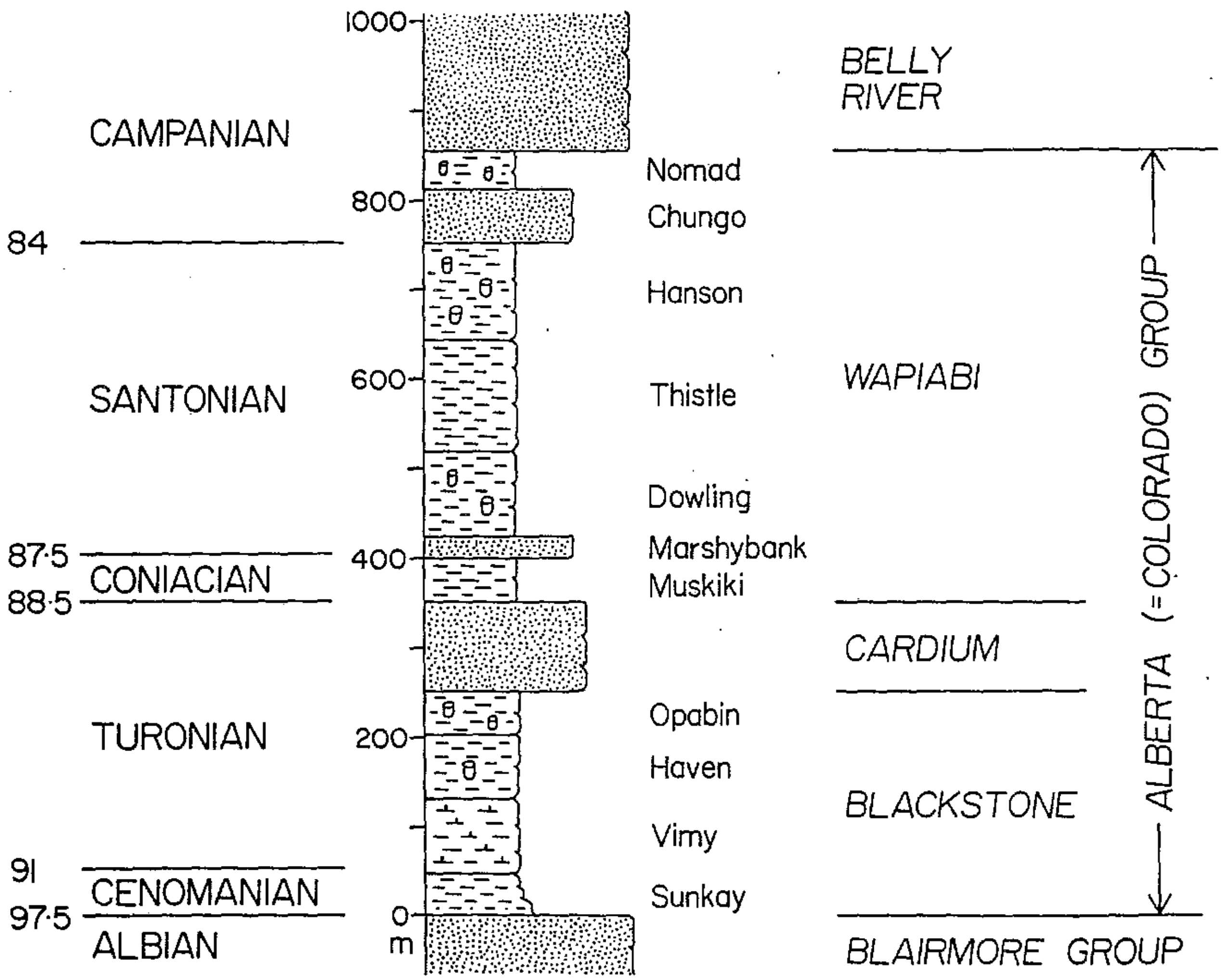

75
5TH MERIDIAN
LIMIT OF
PROGRADATION,
KAKWA MEMBER
KAKWA
Deformed Belt
γ
PINE CREEK
McLEOD
EDSON
NITON
Edmonton
CARROT CREEK
50
PEMBINA
WILLESDEN
GREEN
B.C.
ALBERTA
FERRIER
Alberta
Clearwater R.
GARRINGTON
CAROLINE
RICINUS
CROSSFIELD
LOCHEND
Seebe
25
Calgary
5TH
0 KM 50 100

Figure 2.2. The stratigraphy of the Alberta Group. The Cardium Formation is Upper Turonian in age and rests stratigraphically between the Blackstone Formation and the Wapiabi Formation (after Stott, 1963).

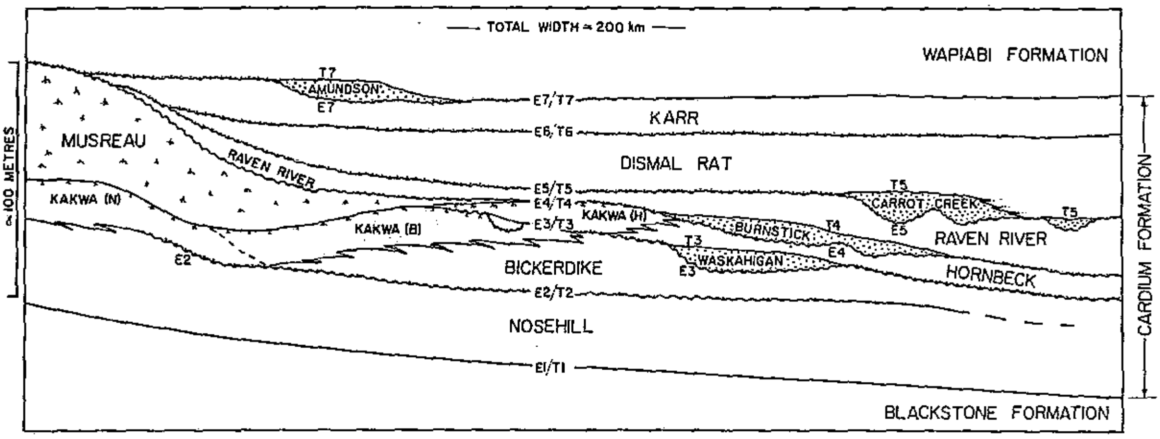

1000
800
600
400
200
0
m
CAMPANIAN
84
SANTONIAN
87·5
CONIACIAN
88·5
TURONIAN
91
CENOMANIAN
97·5
ALBIAN
Nomad
Chungo
Hanson
Thistle
Dowling
Marshybank
Muskiki
Opabin
Haven
Vimy
Sunkay
BELLY RIVER
WAPIABI
CARDIUM
BLACKSTONE
BLAIRMORE GROUP
ALBERTA (=COLORADO) GROUP

The subsurface stratigraphy of the Cardium Formation is based on the recognition of seven basinwide erosional surfaces that are labelled E1 to E7 (Figure 2.3, Plint et al, 1986). These erosional surfaces are discontinuities and divide the Cardium Formation into allostratigraphic units (North American Stratigraphic Code). Each allostratigraphic unit or Member is bounded above and below by at least one erosional surface.

The Burnstick Member is located near the middle of the Cardium Formation and is bounded by the E4 and T4 surfaces (Figure 2.3). In areas where the Burnstick Member is represented by a thin veneer of conglomerate, the E4 and T4 surfaces are co-planar and are shown as E4/T4 (Figure 2.3). To the east, the E4/T4 surface is traced into the basin where it fades into the marine mudstones of the Cardium Formation, while to the west the E4/T4 surface truncates the top of the Kakwa Member. The Kakwa Member has been identified as a shoreface sandstone (Plint et al, 1986) and represents the closest possible paleoshoreface sandstone to the Burnstick Member. The maximum progradation of the Kakwa Member (shoreface) is shown in Figure 2.1.

The Burnstick Member is sandwiched between the marine mudstones of the Hornbeck Member below and the Raven River Member above. It occupies a stratigraphic interval below the Raven River Member sandstones and has been informally termed the Cardium 'B' sandstone by industry.

Figure 2.3. The stratigraphy of the Cardium Formation in southwestern Alberta. The Burnstick Member occurs at a stratigraphic interval midway through the Cardium Formation. It is overlain by the Raven River Member and is underlain by the Hornbeck Member (Plint et al, 1986).


TOTAL WIDTH ≈ 200 km
WAPIABI FORMATION
T7
AMUNDSON
E7
E7/T7
KARR
E6/T6
MUSREAU
RAVEN RIVER
DISMAL RAT
≈100 METRES
E5/T5
T5
CARROT CREEK
T5
KAKWA (N)
E4/T4
KAKWA (H)
KAKWA (B)
E3/T3
BURNSTICK
T4
E5
RAVEN RIVER
T3
E4
E2
WASKAHIGAN
E3
BICKERDIKE
HORNBECK
E2/T2
NOSEHILL
E1/T1
CARDIUM FORMATION
BLACKSTONE FORMATION

2.4 Structure

Most of the subsurface Cardium fields are located in a tectonically undeformed part of the Alberta Foreland Basin. The eastward extent of the thrust belt is located west of the subsurface fields, with the exception of Ricinus which is located on the eastern edge of the disturbed belt (Figure 2.1).

The regional dip of the Cardium sediments in the subsurface ranges from 0.36°W in the northeastern corner of Pembina (Leggitt, 1987) to 0.72°W in the southwestern part of Lochend. This indicates that the dip increases westward across the Alberta Foreland Basin.

The strike of the structural contours on top of the main Cardium sandstone (Roessingh, 1957; Berven, 1966) is roughly equivalent to the regional strike of the Cardium Formation. These structure contours are observed to strike approximately N - S in the southern part of Alberta, while further to the north they strike more NW - SE (Figures 2.4A and 2.4B). It is interesting to note that the strike of the Burnstick Member fields follows this trend as Crossfield (329°-339°) is oriented more N - S than Garrington (318°).

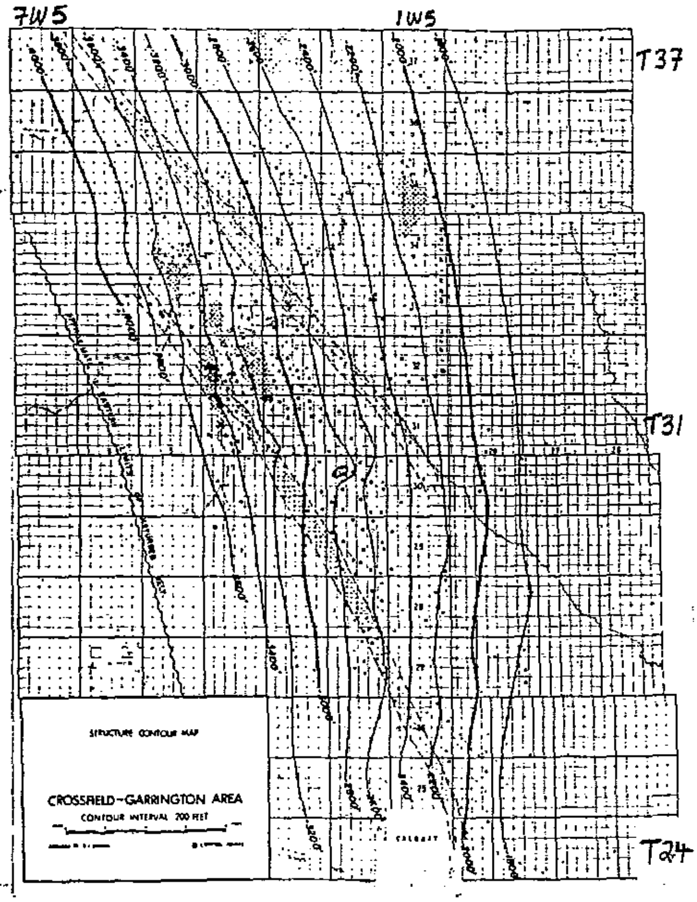
Minor offsets in the strike of the Garrington field in T34/R4W5 indicate the possible existence of faults perpendicular to the strike of the field. Jones (1980) suggests that the offsets in the Garrington field are a result of isostatic adjustment faults (vertical) in the Pre-Cambrian

Figure 2.4. Structural contour maps on top of the main Cardium sandstone as understood in 1966 and 1957.

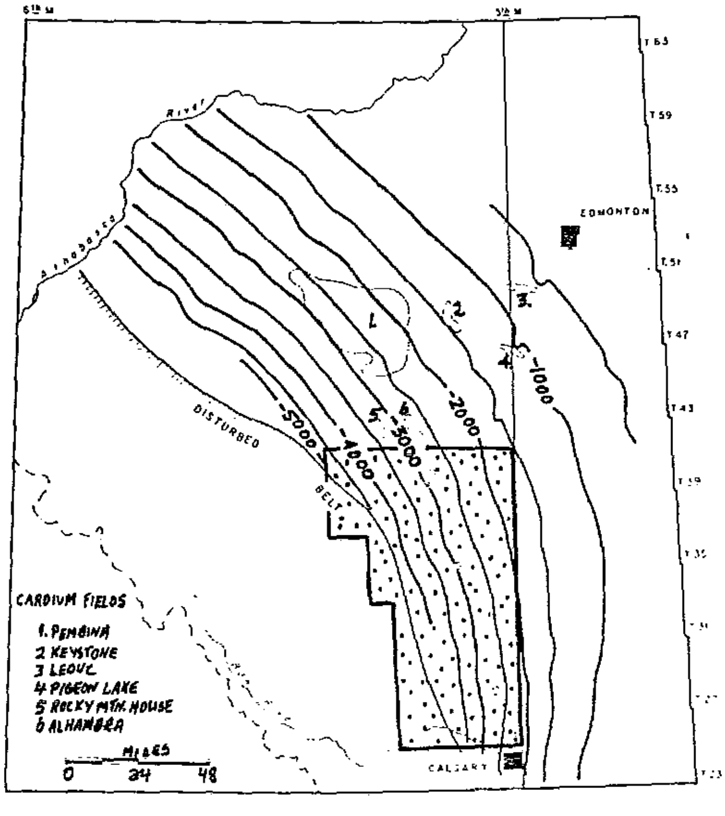
(A). Garrington - Crossfield area (Berven, 1966).

(B). southern Alberta (Roessingh, 1957). The area outlined by dots is the location of the study area.

A


7W5
1W5
T37
T31
T24
STRUCTURE CONTOUR MAP
CROSSFIELD-GARRINGTON AREA
CONTOUR INTERVAL 200 FEET
CALGARY

B


EDMONTON
DISTURBED
BELT
-5000
-4000
-3000
-2000
-1000
CARDIUM FIELDS
1 PEMBINA
2 KEYSTONE
3 LEDUC
4 PIGEON LAKE
5 ROCKY MTN. HOUSE
6 ALHAMBRA
MILES
0 24 48
CALGARY

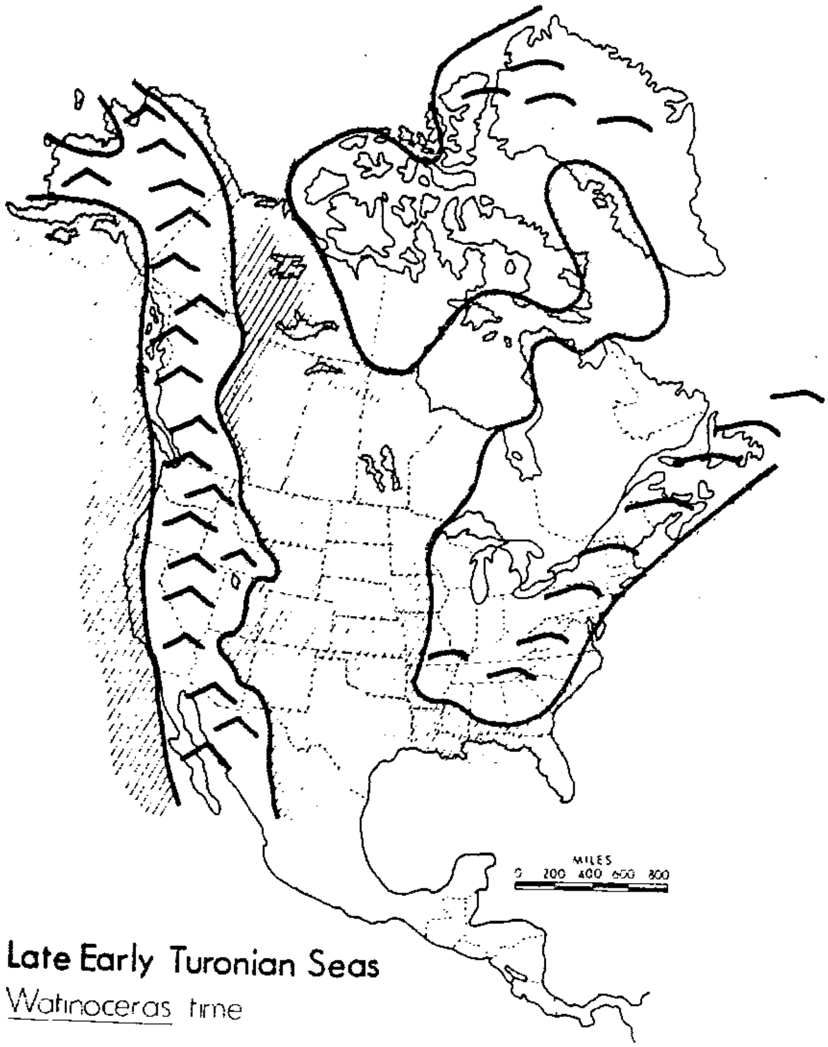
basement rocks. Walker, Eyles, and McLean (pers. comm., 1987) have identified minor thrust faults in the Willesden Green, Ferrier and Carrot Creek fields. These faults, along with the possible existence of faults in the Garrington field, represent the only evidence of folds or faults east of the disturbed belt zone.

2.5 Paleogeography and Paleoclimate

During the Turonian, the Western Interior Seaway of North America extended over 4800 km from Alaska to New Mexico (Figure 2.5), joining the Arctic Ocean with the Gulf of Mexico (Kauffman, 1977). To the west, the seaway was bordered by the rising Cordillera and to the east, was bordered by the Pre-Cambrian shield and the Appalachian Mountains.

In the Upper Turonian, a major global regression occured which caused a sea level drop in the Western Interior Seaway (WIS) (Kauffman, 1977; Haq et al., 1987). During this time, the Cardium Formation was deposited into the Alberta Foreland Basin along the western flank of the WIS. It is believed that the paleoclimatic conditions were mid temperate (Kauffman, 1977) and that the paleolatitude was approximately 10° higher than the present latitude (Couillard and Irving, 1975). The tidal regime of the WIS is poorly understood and is believed to be microtidal to mesotidal (Kauffman, 1977; Rice and Gautier, 1983; Swift and Rice, 1984).

Figure 2.5. Map showing the paleogeography during the late early Turonian. All of Alberta is covered by the Western Interior Seaway and is bordered by the rising Cordillera to the west (Williams and Stelck, 1975).



Late Early Turonian Seas
Watinoceras time

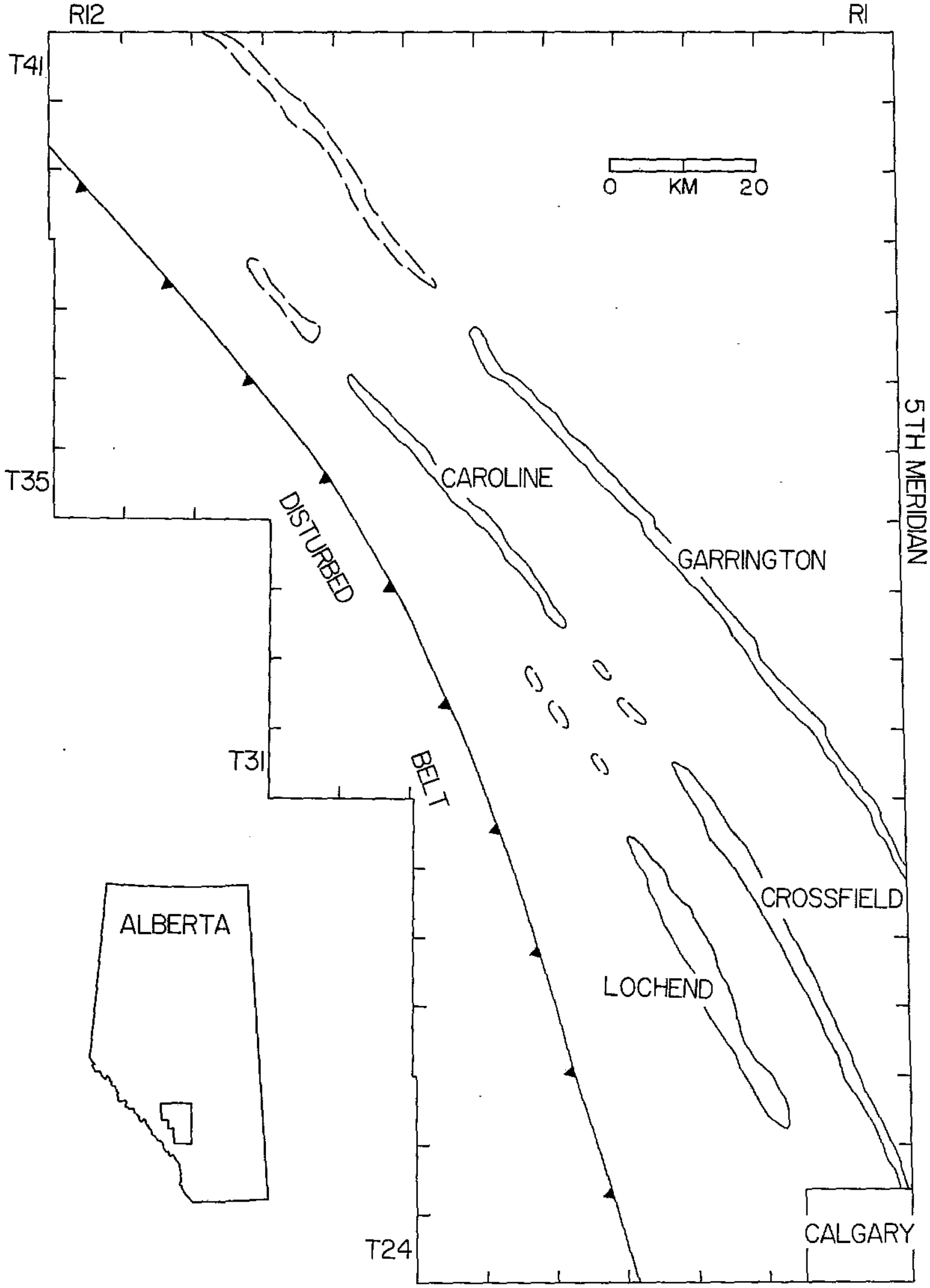
Further paleoclimatic information for the Cretaceous Western Interior Seaway can be obtained by applying complex atmospheric and water circulation models (Barron and Washington, 1982). These models have been used to predict the wind and water circulation patterns of the WIS and include a predicted easterly or variable wind in the central region of Alberta (Parrish et al., 1984).

2.6 Location

The study area is located in south-central Alberta and covers an area of approximately 15,500 km^2 (Figure 2.6). The northern and eastern boundaries of the study area are marked by the T41/T42 contact and the 5th meridian respectively, while the western and southern boundaries are marked by several township and range contacts. The city of Calgary is located in the extreme southeast corner of the study area.

Four Cardium oil fields, Caroline, Crossfield, Garrington and Lochend, are located in the study area (Figure 2.6). These fields are delineated by the occurrence of the Burnstick Member and have long and narrow dimensions. Smaller "pods" of the Burnstick Member are observed in between the four fields and are shown in Figure 2.6 as dashed lines. The four Burnstick Member fields are located south of the other Cardium oil fields (Figure 2.1).

Figure 2.6. The location of the study area in southern Alberta. The Burnstick Member sediments are localized in the areas outlined by solid lines (oil fields) or dashed lines. Most of this study relies on data from Caroline, Crossfield, Garrington and Lochend.


R12
R1
T41
T35
T31
T24
0
KM
20
CAROLINE
GARRINGTON
5TH MERIDIAN
DISTURBED
BELT
CROSSFIELD
LOCHEND
ALBERTA
CALGARY

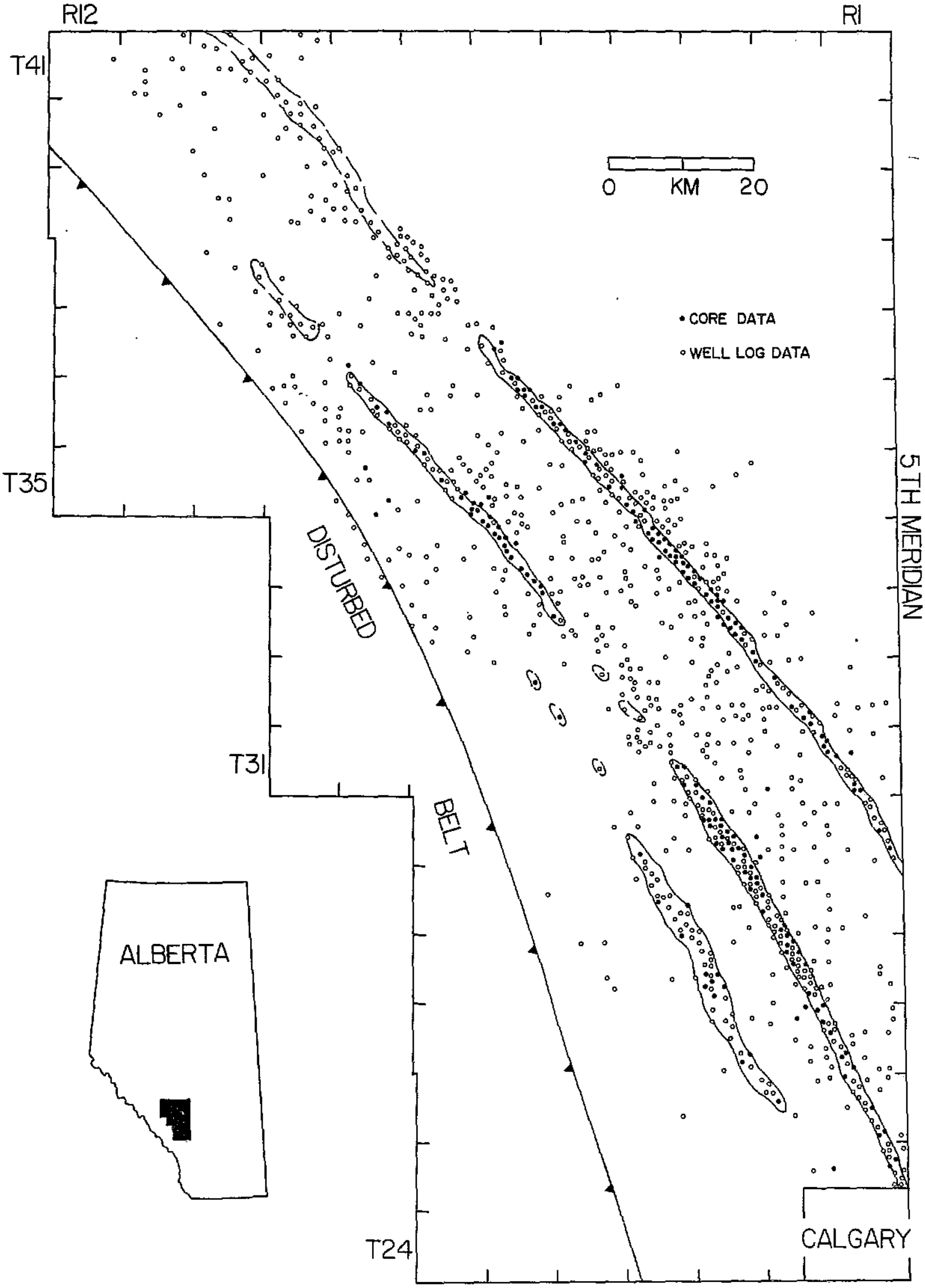
2.7 Data Base

Two different types of data were used in this thesis, drill core and geophysical well logs. The drill core is stored at the Alberta Energy Resources Conservation Board (AERCB) Core Research Center in Calgary, Alberta and consists of 3½" to 4" drill core. A total of 189 cores were examined from the study area, with most of these cores being located in the four fields (Figure 2.7). These cores were logged in detail, emphasizing the grain size, mineralogy, sedimentary structures and trace fossils. This led to the subdivision of the sediments into facies based on the lithological, structural and organic properties of the sediments. Distinct facies sequences are observed in the Burnstick Member package and will be described in Chapter 3.

The drill core data are supplemented by over 800 resistivity well logs printed at Home Oil Co. Ltd in Calgary. The resistivity well logs are used to correlate the Burnstick Member sediments across and between the four fields. Most of the off-field areas, in between the four fields, contains resistivity well log data only and there are no cores (Figure 2.7). The resistivity well logs were chosen over the other types of well logs (e.g. gamma ray log) because they provide the best correlation of the Burnstick Member and the surrounding markers in the study area.

A prominent rightwards deflection (high resistance) is observed on the resistivity well logs at the Burnstick Member

Figure 2.7. The location of the core and well log data used in this study. This data base forms a northwest to southeast trending swath that thins across the study area from 60 kilometers wide in the southeast to 30 kilometers wide in the northwest. Most of the core data is located in the four fields, while the well log data is located in between the fields.


R12
R1
T41
T35
T31
T24
0
KM
20
• CORE DATA
◦ WELL LOG DATA
5 TH MERIDIAN
DISTURBED
BELT
ALBERTA
CALGARY

stratigraphic interval in most of the on-field areas. In contrast, a very subdued rightwards deflection occurs in the off-field areas which indicates that the sediments are of a lower resistance. By correlating the on-field and off-field Burnstick Member drill core data to the corresponding resistivity well log data it is possible to relate the sedimentology to the geophysical data. This makes it possible to make predictions about the sedimentology of the Burnstick Member in areas that have only well log data.

CHAPTER 3: Facies

3.1 Introduction

Ten different facies are identified in the cores that penetrate the Burnstick Member. Of these ten facies, two are observed in the Hornbeck Member, five are observed in the Burnstick Member and three are observed in the Raven River Member.

Some facies consistently appear throughout the entire study area forming a blanket type deposit. These include facies 1A and facies 2A of the Hornbeck Member, and facies 1 of the Raven River Member. The other seven facies have a limited occurrence throughout the study area and are mainly concentrated in the four fields. These include facies 1B, facies 6, facies 6-7B-GS, facies 7 and facies 8 of the Burnstick Member, and facies 6P and facies 1P of the Raven River Member.

3.2 Facies Descriptions

The following is a description of the ten facies observed in the study area. This includes facies 1A and facies 2A of the Hornbeck Member; facies 1B, facies 6, facies 6-7B-GS, facies 7 and facies 8 of the Burnstick Member; and facies 6P, facies 1P and facies 1 of the Raven River Member.

Facies 1: Massive Dark Mudstone

This facies consists of dark grey to black mudstone that has a very massive texture (Figure 3.1A). There is no indication of bioturbation or fissility within these sediments. Rare discontinuous pods of silt are observed within this facies, as are massive siderite beds. The latter are usually 10 to 30 centimeters thick and have fairly sharp contacts with the dark massive mudstone.

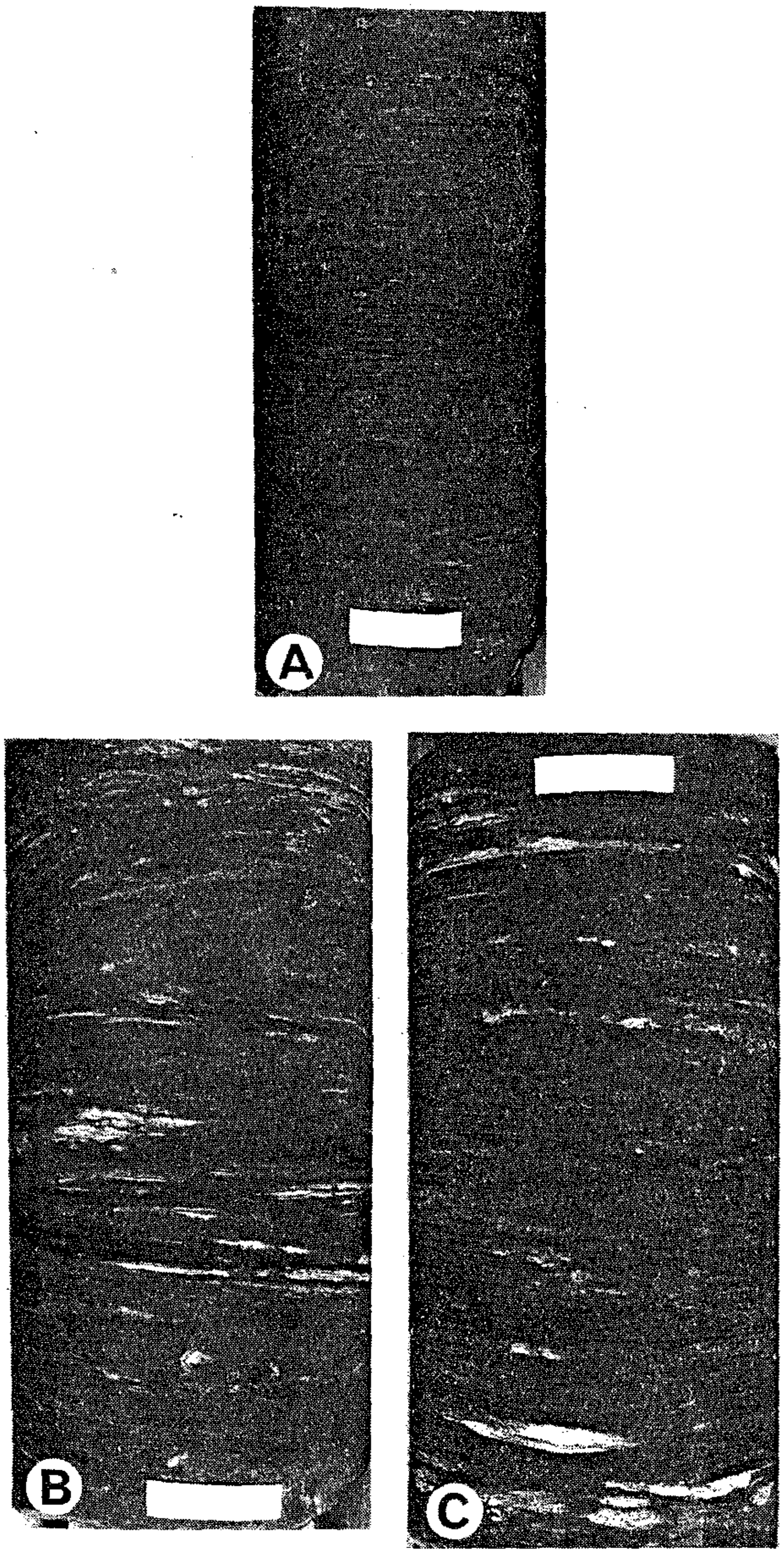
Massive dark mudstone is consistently observed stratigraphically above the coarsening upwards sequence of the Burnstick Member, forming a blanket-like deposit at the base of the Raven River Member. Informally it has been termed the "black blanket" based on its consistent stratigraphic occurrence in the Cardium Formation throughout Southern Alberta (Walker, 1983c).

Facies 1A: Dark Silty Mudstone

This facies consists of dark mudstone with rare, discontinuous silt/sand "pods" or "lenses" (Figures 3.1B and 3.1C). These "pods" or "lenses" consist of gently curving, horizontal laminae that are wave rippled in places and contain silt to vfU sand. The diameter of the "pods" varies from 2 - 8

Figure 3.1. (A). Facies 1 from 10-16-34-6W5 (Caroline) at 8065 feet. (B). Facies 1A from 11-29-34-6W5 (Caroline) at 8105 feet. (C). Facies 1A from 11-29-34-6W5 (Caroline) at 8094 feet.

The scale bars are all 3 centimeters long.


A
B
C

mm, while the "lenses" vary from a few millimeters in length to the width of the core (100 mm). Most of the silt lenses are disturbed by burrowing. The contacts between the silt laminae and the dark mudstone are usually sharp.

This facies occurs below the Burnstick Member and is part of the Hornbeck Member.

Facies 1B: Dark Silty Mudstone with Grit Horizons

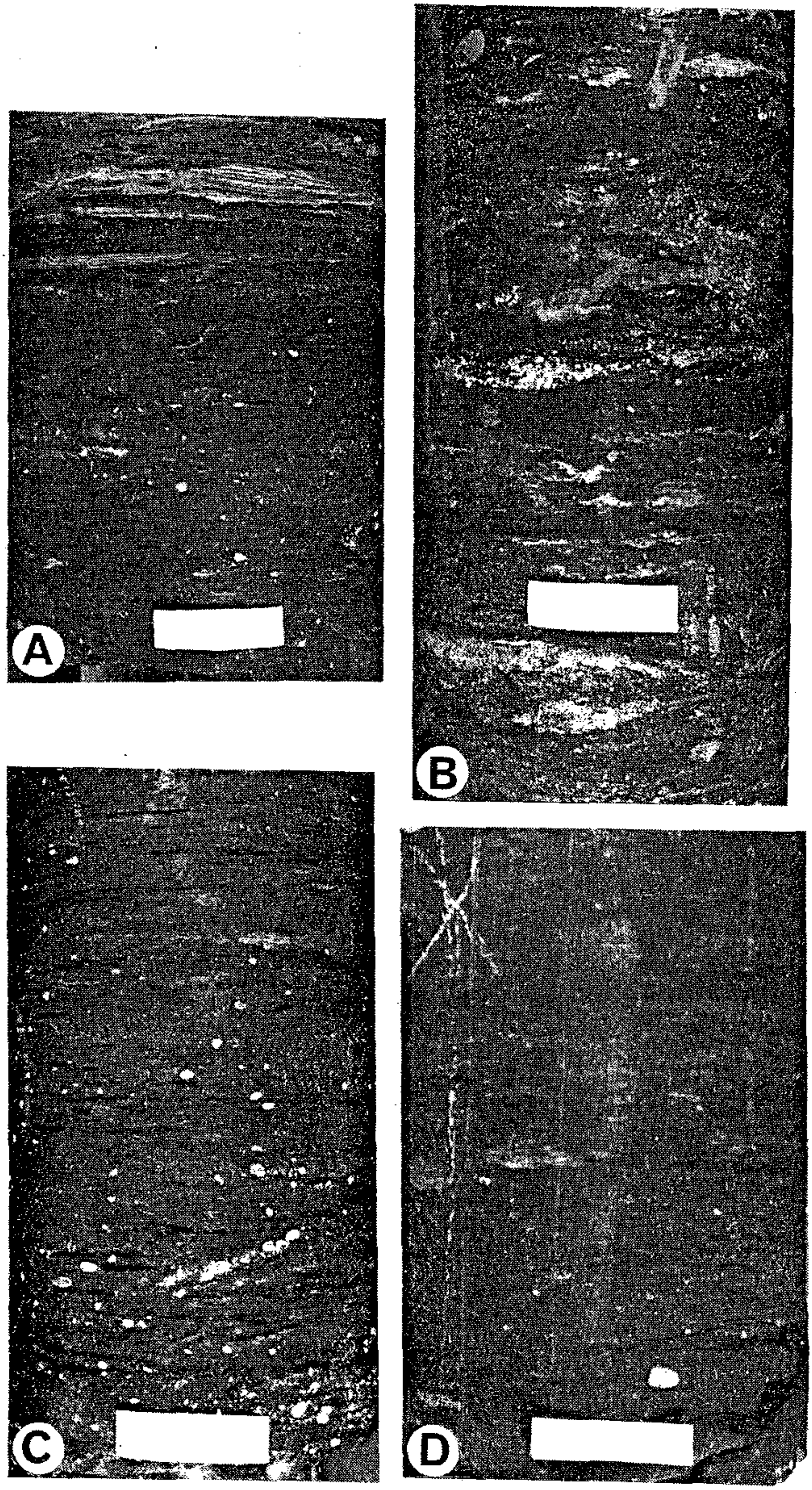
This facies consists of dark silty mudstone (facies 1A) with thin horizons of fL-vcU sand and granules (Figures 3.2A and 3.2B). The grit in this facies constitutes less than 5% of the facies volume and is scattered throughout thin horizons 1 cm to 10 cm thick. Contacts between the grit horizons and the dark silty mudstone are gradational, suggesting a moderate amount of bioturbation. Grain to grain contacts in the grit horizons are rare.

This facies is very similar to facies 6 in the sense that it consists of scattered grit embedded in a background facies 1A. However, two characteristics distinguish facies 1B from facies 6, including the percentage of grit (<5%) and the absence of pebbles in facies 1B.

Facies 1B is most commonly observed as the "off-field" equivalent of the Burnstick Member and rests stratigraphically on top of the Hornbeck Member. The average thickness of facies 1B is 0.28 meters. This facies can also occur

Figure 3.2. (A). Facies 1B from 13-22-34-6W5 (Caroline) at 2417 meters. (B). Facies 1B from 11-27-35-5W5 (Garrington) at 7083 feet. (C). Facies 1P from 6-25-29-3W5 (Crossfield) at 6613 feet. (D). Facies 1P from 11-4-35-4W5 (Garrington) at 2040 meters.

All of the scale bars are 3 centimeters in length.


A
B
C
D

below the Hornbeck Member/Burnstick Member contact in some cored "on-field" wells.

Facies 1P: Dark Mudstone with Scattered Grit

This facies is very similar to facies 1, except that it contains rare scattered sand grains, granules or pebbles. It contains "floating" clasts of fL-vcU sand, granules and pebbles that are dispersed throughout the dark mudstone (Figures 3.2C and 3.2D). Typically, these clasts constitute less than 5% of the facies volume and are usually coarsest towards the stratigraphic base of the facies. This defines a fining upwards trend that is capped by the last occurrence of a sand grain or pebble.

This facies is consistently observed stratigraphically above the Burnstick Member. It differs from facies 1B in that the grit is not concentrated in layers and that it has a background facies 1 instead of a background facies 1A. The maximum thickness of facies 1P is 1.85 m, while the average thickness of this facies is 0.33 m.

Facies 2A: Dark Silty Mudstone with Siltstone Beds

This facies consists of discontinuous and continuous siltstone beds embedded in a dark silty mudstone (Figures 3.3A and 3.3B). Facies 2A is very similar to facies 1A with the only difference being the presence of siltstone beds in facies 2A.

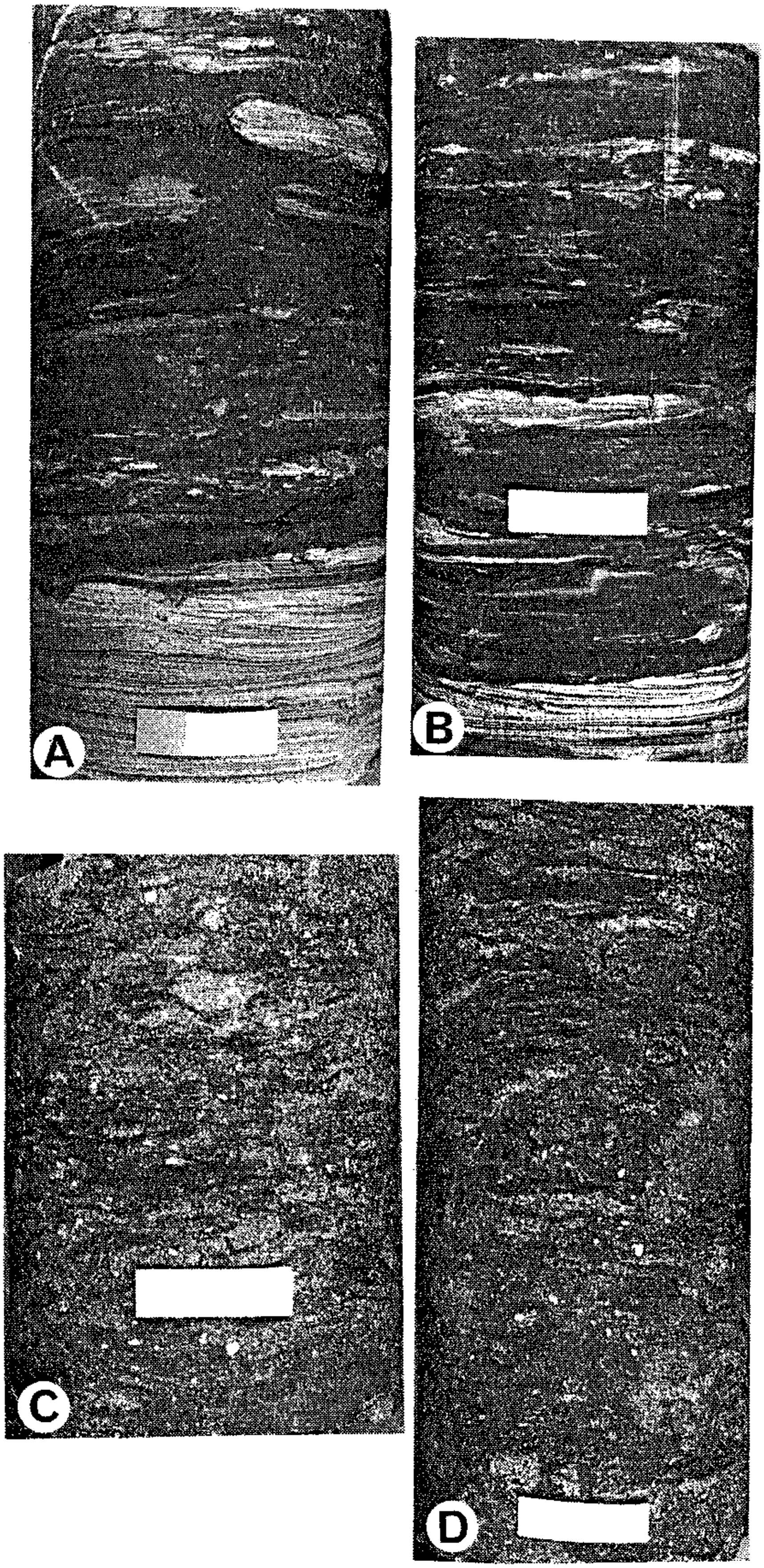
The siltstone beds of facies 2A are composed of parallel, gently curving siltstone laminae that are wave rippled in places and are sometimes separated by mudstone laminae. The thickness of the individual laminae varies from <1 mm to 5 mm.

These laminae are grouped together to form siltstone beds that are between 1 - 8 cm thick. Some of the thicker beds (>5 cm) are continuous across the width of the core (Figure 3.3A), while the other siltstone beds form discrete pods or lenses, 2 - 7 cm across (Figure 3.3B). The discontinuous siltstone beds show evidence of bioturbation with recognizable trace fossils including Thalassinoides and Teichichnus. Contacts between the siltstone beds and the surrounding dark silty mudstone are usually sharp.

In general, facies 2A consists of approximately 20% siltstone beds and 80% dark silty mudstone. Facies 2A is observed in some cores through the Hornbeck Member, which occurs stratigraphically below the Burnstick Member. In contrast to Walker's facies 2 (1983c), which contains 1 mm to 5 mm thick continuous siltstone beds, facies 2A siltstone beds are thicker and can also be discontinuous.

Figure 3.3. (A). Facies 2A from 4-13-35-7W5 (Caroline) at 8272 feet. (B). Facies 2A from 12-33-36-8W5 (Caroline) at 8546 feet. (C). Facies 6 from 16-16-30-3W5 (Crossfield) at 6707 feet. (D). Facies 6 from 6-13-29-4W5 (Lochend) at 2229 meters.

The scale bars are 3 centimeters in length.


A
B
C
D

Facies 3, 4 and 5

Facies 3, 4 and 5; bioturbated muddy siltsones, pervasively bioturbated muddy sandstones and bioturbated sandstones (Walker, 1983c), do not occur within the stratigraphic level of the Burnstick Member. However, the background sediments in facies 6 of the Burnstick Member consist of facies 3 near the base and facies 5 near the top. These facies were first described by Walker (1983c) in a study of the Raven River Member sediments in the Caroline -- Garrington area.

Facies 6: Speckled Gritty Mudstone

This facies (Walker, 1983c) consists of an intensely bioturbated mixture of silt, sand, granules and pebbles set in a dark mudstone (Figures 3.3C and 3.3D). The diagnostic feature of this facies is its speckled appearance that is produced by the difference in grain size between the "floating" clasts and the background sediments. The "floating" clasts are commonly pebbles, granules or sand grains (quartz and chert) that are dispersed throughout the facies. These clasts are an order of magnitude larger than the background sediments which consist of well bioturbated silt and fine sand set in a dark mudstone. The largest "floating" clast observed in facies 6 is an 22 mm pebble.

The coarsest clasts, such as the pebbles and the granules, are usually observed in the basal one third of this facies. In the upper two thirds of the facies, the "floating" clasts are commonly medium to coarse grained sand grains. This vertical change in "floating" clast grain size is superimposed on an overall coarsening upwards trend of the background sediments. The background sediments in facies 6 pass vertically from Walker's (1983c) facies 3 at the base to Walker's (1983c) facies 5 near the top.

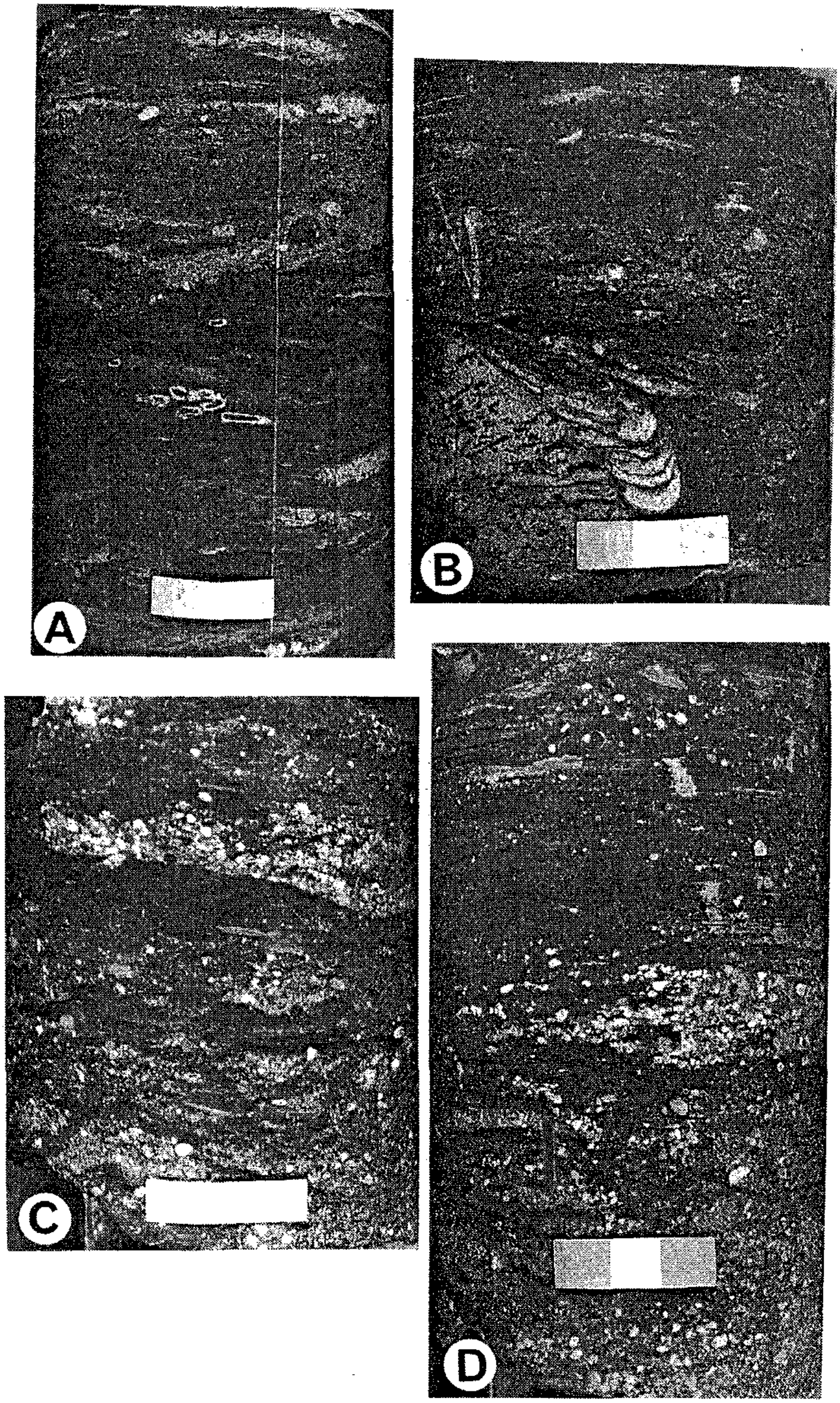
As mentioned previously, this facies is intensely bioturbated, giving it a well stirred appearance. Recognizable trace fossils are not ubiquitous in this facies, but when observed include <u>Terebellina</u> (Figure 3.4A), <u>Teichichnus</u> (Figure 3.4B), <u>Thalassinoides</u>, <u>Planolites</u> and <u>Skolithos</u>.

Facies 6 most commonly occurs stratigraphically on top of the Hornbeck Member/Burnstick Member contact and represents the lowermost facies of the Burnstick Member. It is distinguished from the facies below the contact by its speckled nature and its coarseness. Facies 6 has an average thickness of 0.90 m and reaches a maximum thickness of 3.83 m in Crossfield.

The lower contact between facies 6 and the underlying facies 1A or facies 2A can be extremely sharp, as is the case in the Crossfield and Caroline fields, or it can be gradational to sharp as observed in cores from the Lochend and Garrington fields. The upper contact between facies 6 and

Figure 3.4. (A). Terebellina burrows just below the facies 1A/ facies 6 contact in 10-1-35-7W5 (Caroline) at 2520 meters. (B). Teichichnus burrow in facies 6 sediments of 10-1-35-7W5 (Caroline) at 2519 meters. (C). Facies 6P in 10-24-31-2W5 (Garrington) at 1825 meters. (D). Facies 6P/facies 1P contact in 10-5-29-2W5 (Crossfield) at 6761 feet. The contact is located halfway in the core photograph above the highest coarse sand lense.

The scale bars are 3 centimeters in length.


A
B
C
D

the overlying Burnstick Member sediments is usually gradational.

Facies 6P: Pebbly Dark Mudstone

This facies consists of sand, granules and pebbles "stirred" into a background facies 1 (Figures 3.4C and 3.4D). The mixing is so intense that the original layering is rarely observed. Where observed, the original layering consists of 2 - 10 cm beds of sand, granules and pebbles that have sharp contacts with the background facies 1. Facies 6P is totally bioturbated, but no recognizable distinct trace fossils were observed.

Two unique characteristics separate this facies from the other facies observed in the study area. First, this facies contains the coarsest material observed in the Burnstick Member coarse sediment package and, secondly, this facies exhibits an excellent fining upwards sequence. Pebbles up to 15 mm in diameter are commonly observed at the base of this facies grading upwards into granules and sand.

The clasts observed in facies 6P are subrounded to rounded quartz and chert grains that are randomly oriented in the massive dark mudstone. These clasts constitute approximately 5% to 40% of the facies volume. In some cores, subangular mud clasts, less than 2 cm in diameter, are observed near the base of facies 6P.

Facies 6P sits stratigraphically on top of the Burnstick Member/Raven River Member contact. The average thickness of facies 6P is 0.25 m. The lower contact between facies 7 or facies 8, and facies 6P can be gradational to sharp, while the upper contact with facies 1P is very gradational.

In contrast to facies 6, facies 6P contains a greater percentage of granules and pebbles, it is set in a muddier background facies and exhibits a fining upwards sequence instead of a coarsening upwards sequence.

Facies 6-7B-GS: Interbedded Mudstone, Sandstone and Siderite

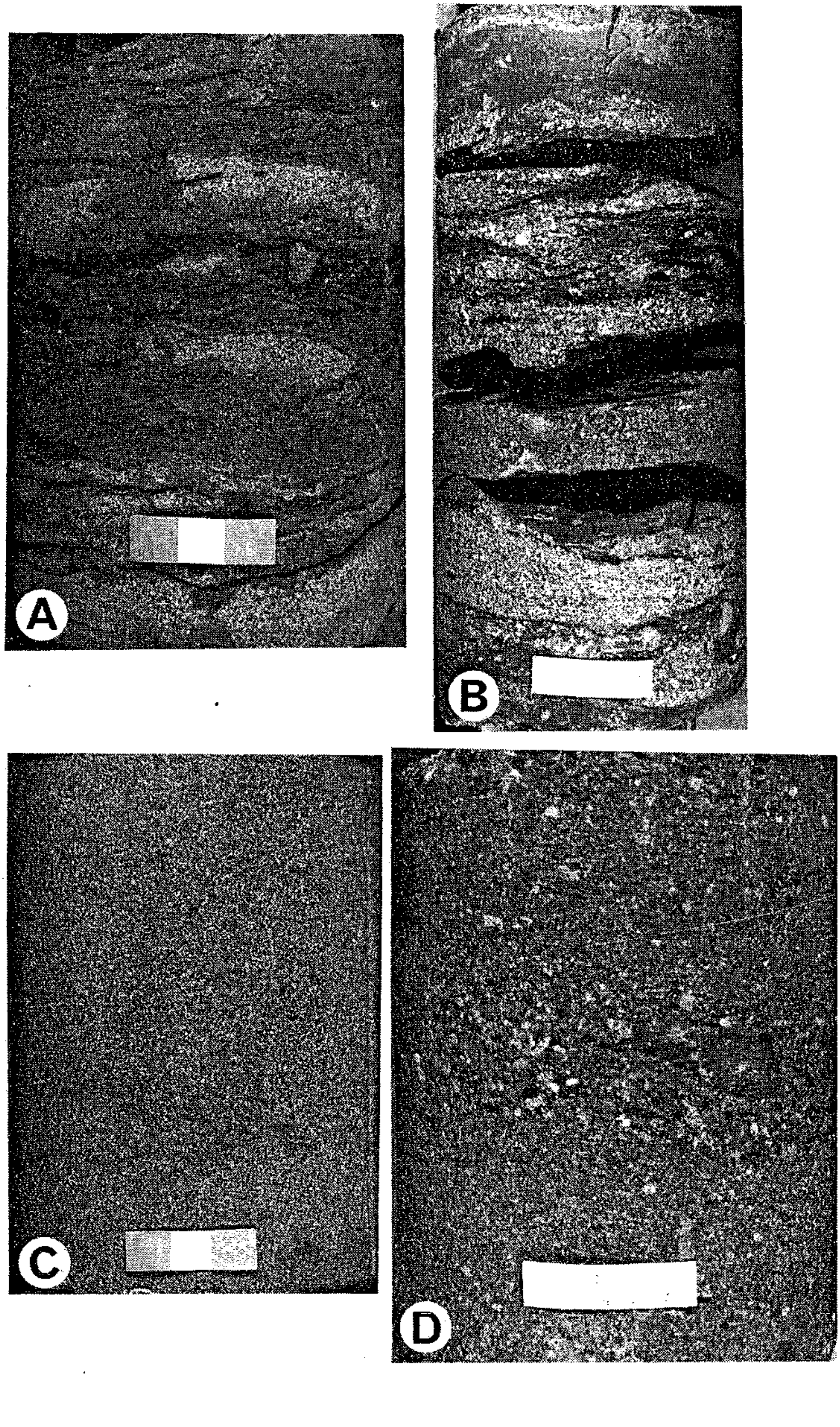
This facies consists of interbedded speckled gritty mudstone (facies 6), bioturbated sandstone (facies 7B) and gritty siderite (Figures 3.5A and 3.5B). The interbeds of speckled gritty mudstone, bioturbated sandstone and gritty siderite are 2 - 35 cm thick, moderately bioturbated and have gradational to sharp contacts with the surrounding interbeds.

Speckled gritty mudstone interbeds consist of scattered sand grains (fL-vcU) embedded in a moderately bioturbated background silty mudstone. Bioturbation of these interbeds is not as intense as the bioturbation of facies 6 sediments below facies 6-7-GS. Distinct mud laminae, 1 - 3 cm thick, are frequently preserved within these interbeds.

Bioturbated sandstone (facies 7B) interbeds consist of fL-cU sand, with scattered "shreds" of mudstone 1 - 4 cm in diameter. These interbeds are moderately bioturbated and

Figure 3.5. (A). Facies 6-7B-GS from 10-1-35-7W5 (Caroline) at 2518 meters. (B). Facies 6-7B-GS from 2-3-37-6W5 (Garrington) at 7175 feet. Four interbeds, from bottom to top, include facies 6, facies 7B, facies 6 and a gritty siderite (GS). (C). Facies 7 from 12-21-34-6W5 (Caroline) at 2457 meters. (D). Facies 7 from 10-24-31-2W5 (Garrington) at 1826 meters. Notice the difference in grain size between (C) and (D).

The scale bars are 3 centimeters in length.


A
B
C
D

are preserved in many different shapes, such as continuous beds, discontinuous beds, pods and lenses. Contacts between the bioturbated sandstone interbeds and the surrounding interbeds are relatively sharp.

Gritty siderite interbeds are a yellow-brown colour and are a lot denser than the surrounding sediments. These interbeds contain less sand and are not as commonly observed as the other two types of interbeds. The sand within the gritty siderite interbeds is fL-mU and can be scattered throughout the facies or concentrated in pods or lenses.

Facies 6-7B-GS is observed in most Burnstick Member cores and represents a transitional facies between the speckled gritty mudstone facies (facies 6) and the non-bioturbated sandstone facies (facies 7). The thickness of facies 6-7B-GS varies from 0.15 - 3.04 m, and has an average thickness of 0.87 m.

Each occurrence of facies 6-7B-GS has a distinct appearance with no two occurrences looking alike. The number of interbeds observed in facies 6-7B-GS throughout the study area varies from 3 to 22. Many of the contacts between the interbeds are diffuse, which can make it difficult to accurately separate the three types of interbeds.

Facies 7: Non-bioturbated Sandstone

Facies 7 consists of non-bioturbated, moderately well sorted, fU-vcU sand with variable amounts of granules and pebbles (Figures 3.5C and 3.5D). In places, the sandstone exhibits medium scale cross bedding (Figures 3.6A and 3.6B), and can also be horizontally laminated. The percentage of granules and pebbles does not exceed 30%, with the greatest concentrations occuring towards the stratigraphic top of this facies. Rare mudstone laminae are observed towards the stratigraphic base of this facies. Overall, facies 7 defines an excellent coarsening upwards sequence, passing from fine sand with mudstone at the base up into coarse, pebbly sandstone near the top.

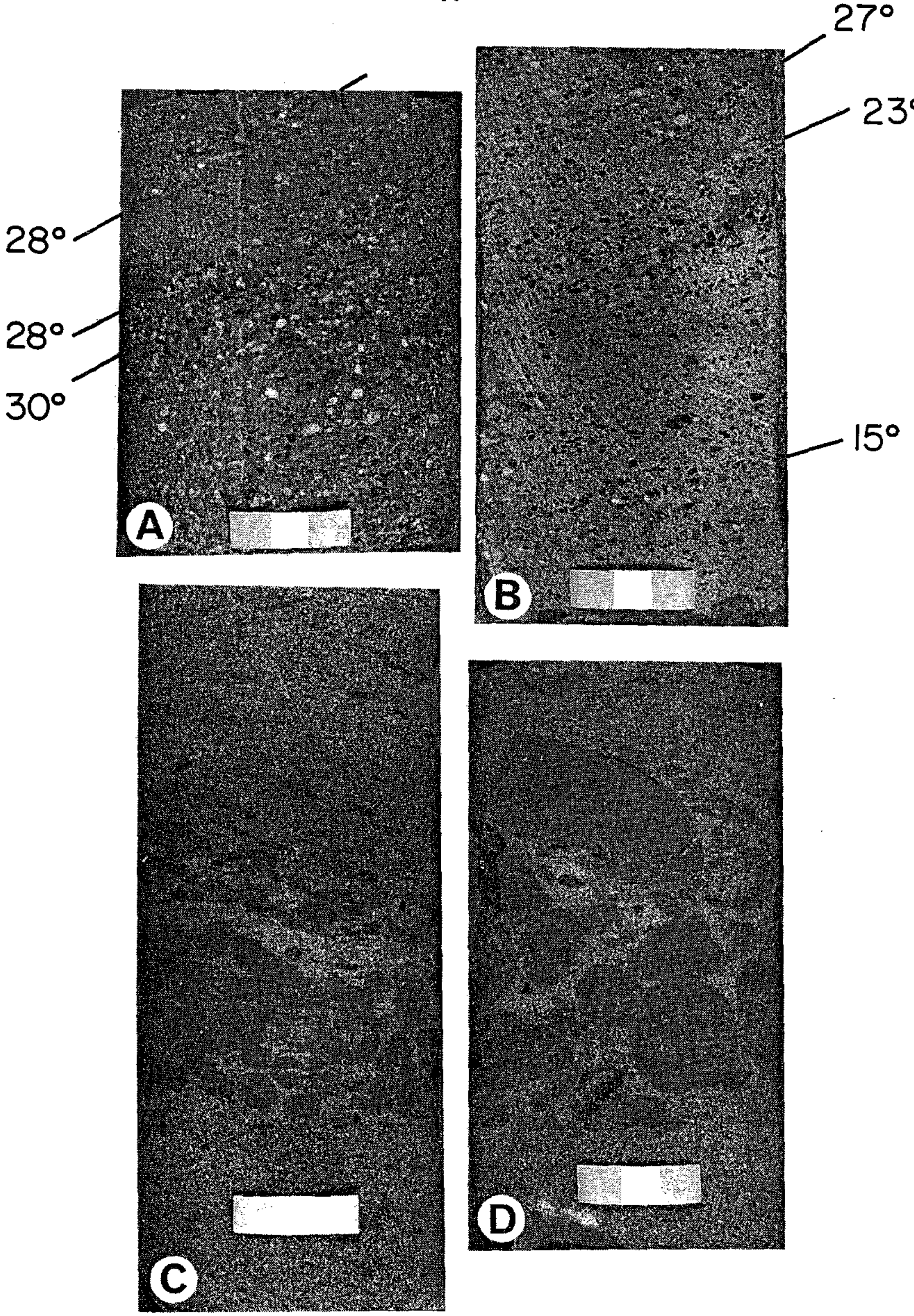
Textural differences, between various laminae, are very common in this facies and have a tendency to highlight the bedding characteristics of the sandstone. Trough cross bed sets, up to 30 cm thick, are observed in approximately 20% of cored facies 7 sediments (Figures 3.6A and 3.6B). The cross bedding can be difficult to see in some cores especially when there is little textural variation between individual laminae.

The magnitude of the cross bed dip changes vertically through the core, but rarely exceeds an angle of 20 degrees, suggesting that these are trough cross beds. Horizontally laminated sandstones are also highlighted by textural differences between individual laminae but are less frequently observed than cross bedded sandstones.

Another diagnostic characteristic of facies 7 is the occurrence of zones of ripped up mud clasts (Figures 3.6C and 3.6D). These mud clasts are well rounded, 2 mm to 45 mm in

Figure 3.6. (A). Cross bedded facies 7 in 12-21-34-6W5 (Caroline) at 2456 meters. The textural differences in the sandstone highlight the cross bedding. (B). Cross bedded facies 7 in 8-26-27-2W5 (Crossfield) at 6734 feet. (C). A seven centimeter bed of ripped up, sideritized mud clasts from facies 7 in 11-14-34-4W5 (Garrington) at 6502 feet. (D). A nine centimeter bed of ripped up, sideritized mud clasts in 11-14-34-4W5 (Garrington) at 6504 feet.

The scale bars are 3 centimeters long.


28°
28°
30°
A
27°
23°
15°
B
C
D

diameter, sideritized, concentrated in beds or horizons up to 25 cm thick and constitute up to 75% of the volume of the horizon. The mud clast horizons commonly occur in the upper half of facies 7 and are observed in approximately 30% of the cored facies 7 sediments.

Facies 7 constitutes the upper part of the Burnstick Member and is best developed in the central to northern parts of the fields (Caroline, Crossfield, Garrington and Lochend). The average thickness of facies 7 is 0.85 m, with a maximum thickness of 4.16 meters from a cored well in Caroline. These sandstones display a wide variety of characteristics and are coarser than the facies 7 sandstones of the Raven River Member.

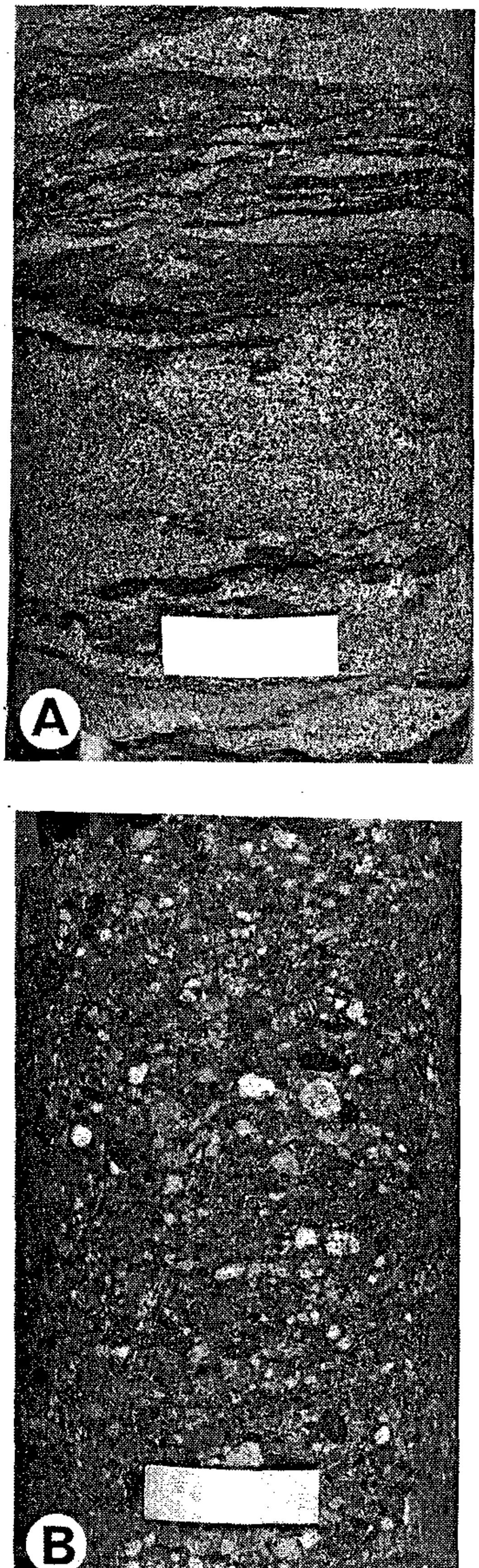
Facies 7B: Bioturbated Sandstone

This facies consists of bioturbated, moderately well sorted, fL-cU sand with scattered mudstone "shreds" 1 cm to 4 cm in diameter (Figure 3.7A). Bioturbation is indicated by the rare occurrence of Skolithos and Teichichnus trace fossils, the discontinuous nature of the sandstone beds and the gradational contact between the sandstone beds and the surrounding sediments. Individual sand laminae are rarely observed in this facies.

Facies 7B is most commonly observed between facies 6 and facies 7, forming part of facies 6-7B-GS. The thickness of facies 7B ranges from 5 - 35 cm. It can be distinguished

Figure 3.7. (A). Facies 7B in 1-23-34-4W5 (Garrington) at 6458 feet. (B). Facies 8 in 8-14-31-4W5 (Crossfield) at 7010 feet. This conglomerate is matrix supported.

The scale bars are 3 centimeters long.



from facies 7 based on the degree of bioturbation and the absence of granules and pebbles.

Facies 8: Conglomerate

This facies consists of matrix supported conglomerate that has between 30% to 60% framework clasts embedded in a sandy matrix (Figure 3.7B). The framework clasts consist of well rounded quartz or chert granules and pebbles set in a medium to coarse grained sandy matrix. The intermediate diameter of the quartz and chert clasts varies from 2 - 20 mm. No structures are observed in this facies.

Facies 8 rests gradationally on top of facies 7 and is truncated at the top by the Burnstick Member/Raven River Member contact. It is the upper most facies of the Burnstick Member. This facies is observed in approximately 15% of the cored wells throughout the study area and reaches a maximum thickness of 2.43 meters in northern Crossfield.

3.3 Vertical Facies Sequences

Three vertical facies sequences are observed in the cores that penetrate the Burnstick Member and the lower Raven River Member. Two of the vertical facies sequences are observed in the on-field cores, while the other vertical facies sequence is observed in the off-field cores. In both the on-field and the off-field areas, the sediments that comprise the vertical facies sequences are termed coarse sediment packages.

On-field and off-field cores are defined based on the thickness of the Burnstick Member sediments. This is determined by measuring the Burnstick Member well log response for a corresponding core. If the Burnstick Member well log response is greater than three feet in thickness, the sediments are defined as on-field, while a Burnstick Member well log response less than three feet in thickness defines an off-field core. Of the 189 cores used in this study, 174 are from on-field positions, while only 15 are from off-field positions (Appendix). This results in a data base that is biased towards the on-field facies relationships.

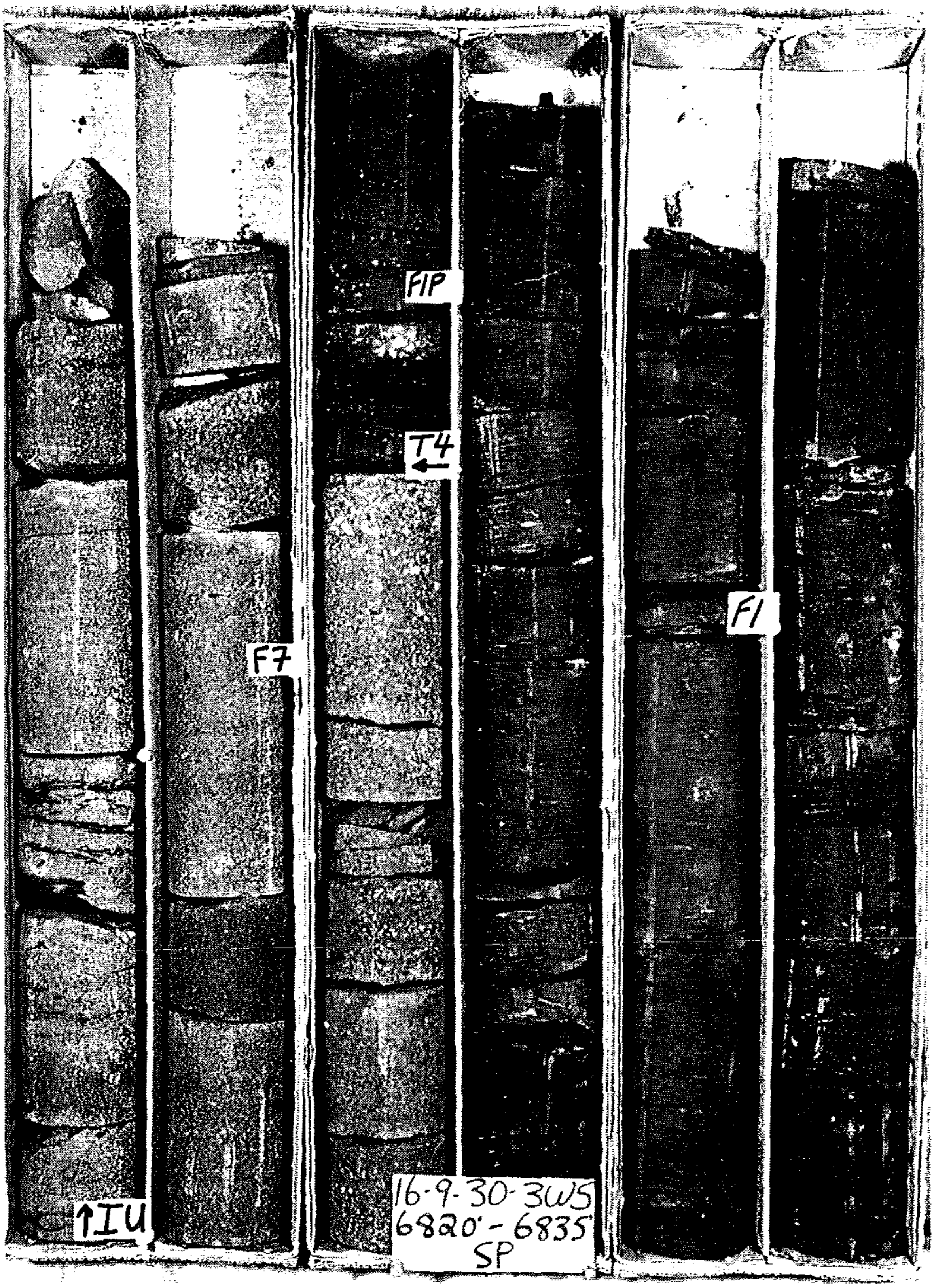
On-Field Vertical Facies Sequences

Within the on-field areas, a coarse sediment package is consistently observed in the Burnstick Member/lower Raven River Member stratigraphic interval (Figure 3.8). This coarse sediment package is subdivided into a lower vertical facies sequence and an upper vertical facies sequence. The lower vertical facies sequence consists of facies 6, facies 6-7B-GS, facies 7 and facies 8 from the Burnstick Member, while the upper vertical facies sequence consists of facies 6P, facies 1P and facies 1 from the lower Raven River Member. Figure 3.9 shows the relationships between the facies of the

Figure 3.8. The next two pages show a typical example of the coarse sediment package that is consistently observed in the on-field, Burnstick Member/lower Raven River Member stratigraphic interval. This core is from 16-9-30-3W5 in Crossfield and covers the interval from 6820 feet to 6850 feet. The stratigraphic top is in the top right hand corner of the core box. Each core sleeve is approximately 75 cm long.

The IU tag near the central part of Figure 3.8 stands for facies 6-7B-GS.


E4
GS
↑IU
FIA
F6
16-9-30-3W5
6835'-6850'
SP


FIP
T4
F7
F1
↑IU
16-9-30-3W5
6820'-6835'
SP

two vertical sequences and also presents the average thickness of the facies from the four fields.

The Burnstick Member vertical facies sequence (BM sequence) is characterized by a relatively sharp lower contact with the Hornbeck Member below and a more gradational contact with the Raven River Member above. These two contacts are discussed in more detail in section 3.4.

The contacts between the four facies within the BM sequence are gradational and are usually disturbed by bioturbation. Apart from the concentration of coarse clasts in the basal part of the BM sequence, the sequence becomes sandier and coarser upwards. There is also a decrease in the amount of bioturbation from the base to the top of the BM sequence.

Most of the BM sequences in the Caroline, Crossfield and Lochend fields are complete, in the sense that all four of the facies are observed. In contrast, most of the BM sequences in the Garrington field are incomplete, as they lack a facies 8 and they also have a thin, poorly developed facies 7 (Figures 3.10 and 3.11).

The second vertical facies sequence, termed the lower Raven River Member facies sequence (LRRM sequence), comprises the upper part of the coarse sediment package in the on-field areas. It rests stratigraphically on top of the BM sequence (Figure 3.9), and it consists of facies 6P, facies 1P and facies 1. In contrast to the coarsening upward BM sequence, the LRRM sequence fines upwards from a pebbly mudstone at the

Figure 3.9. Composite facies sequence for the Burnstick Member/lower Raven River Member coarse sediment package. The average thickness of the facies is determined from measurements in 173 on-field cores from the study area. Note the two vertical facies sequences: the Burnstick Member facies sequence (BM) and the lower Raven River Member facies sequence (LRRM).

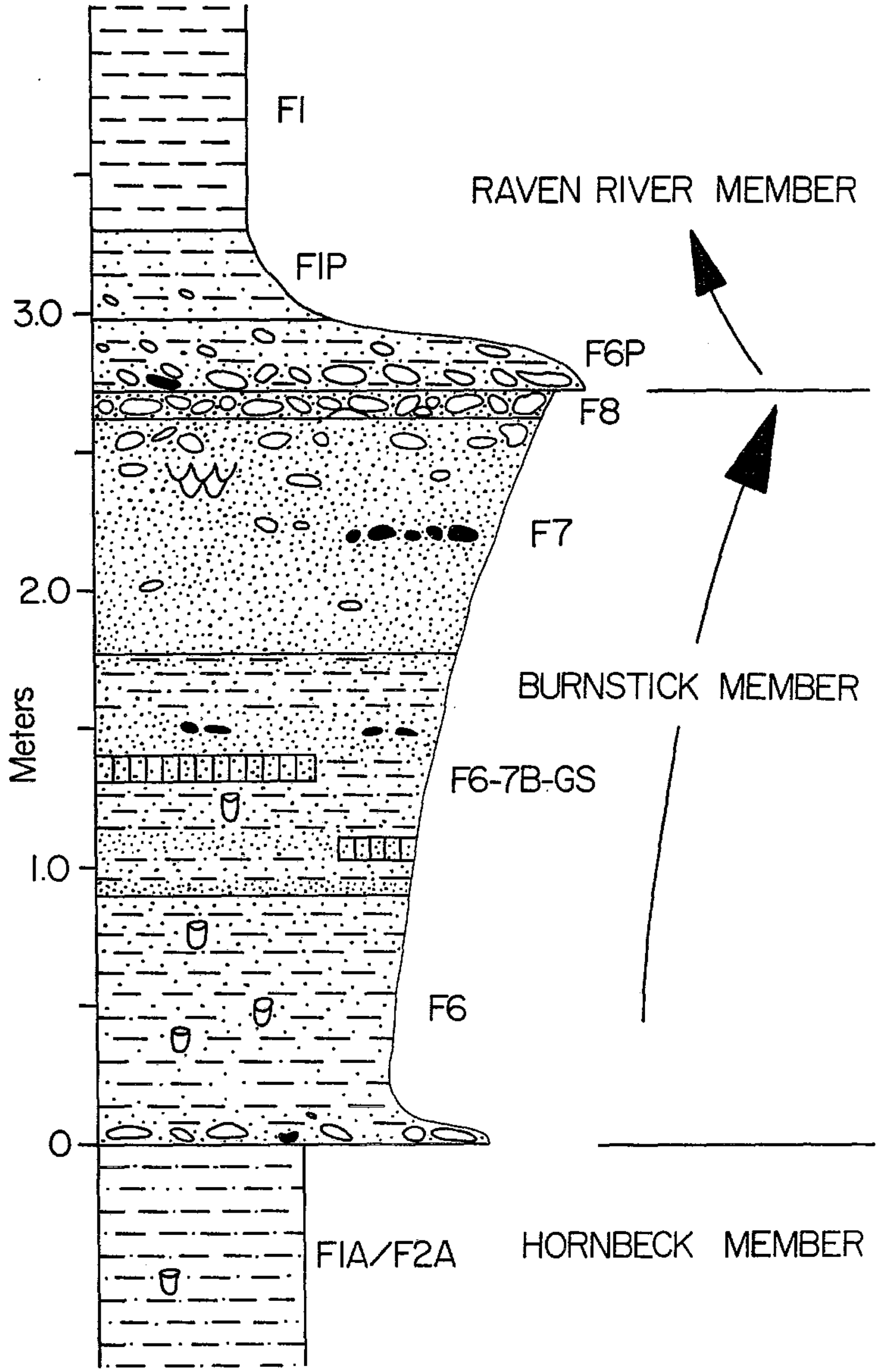

F1
RAVEN RIVER MEMBER
F1P
3.0
F6P
F8
F7
2.0
BURNSTICK MEMBER
Meters
F6-7B-GS
1.0
F6
0
F1A/F2A
HORNBECK MEMBER

Figure 3.10. Composite facies sequences for Caroline, Crossfield, Garrington and Lochend showing the average thickness of the facies in each field. Note the similarity between the vertical facies sequences in Caroline and Crossfield, and compare them to the vertical facies sequences of Garrington and Lochend.

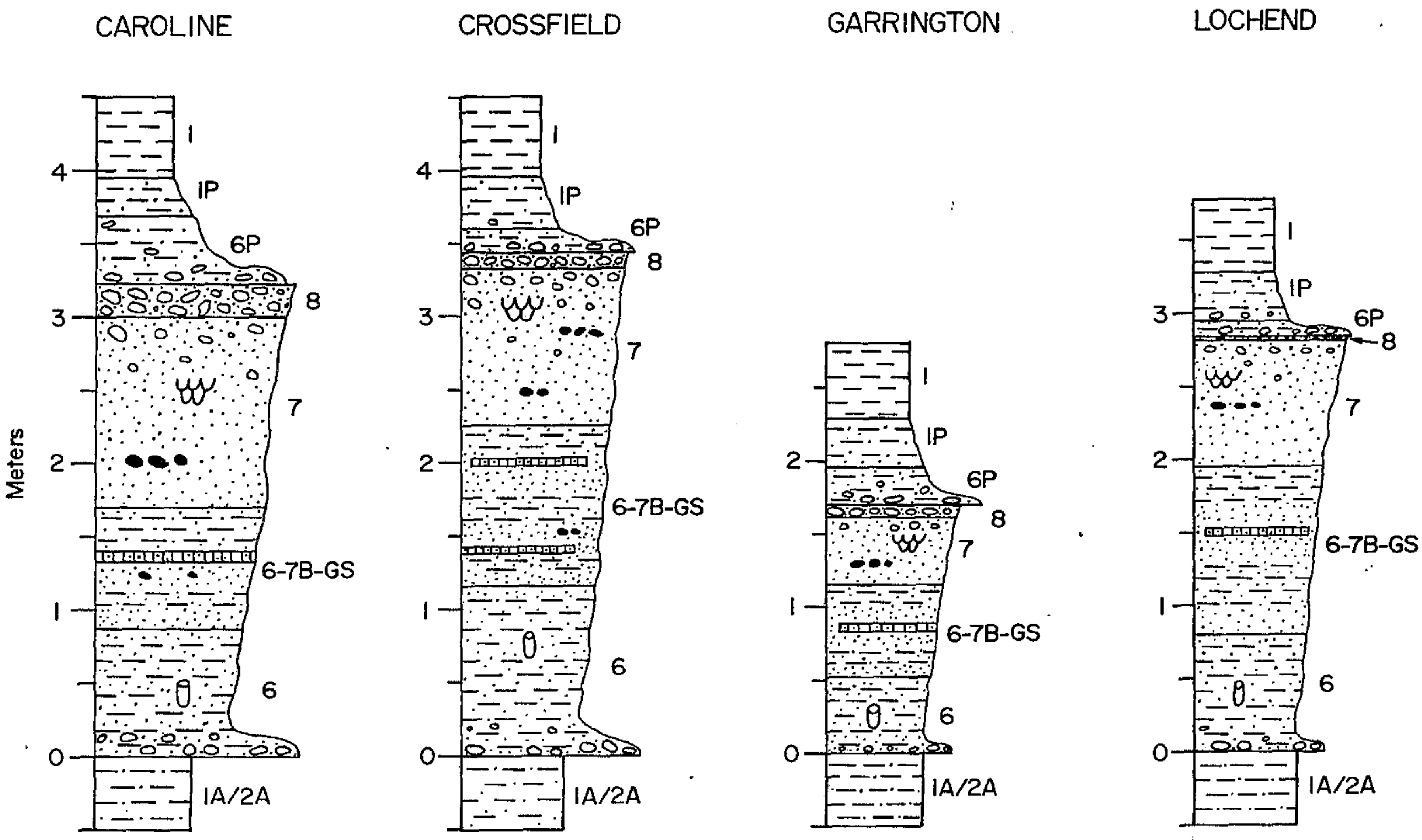
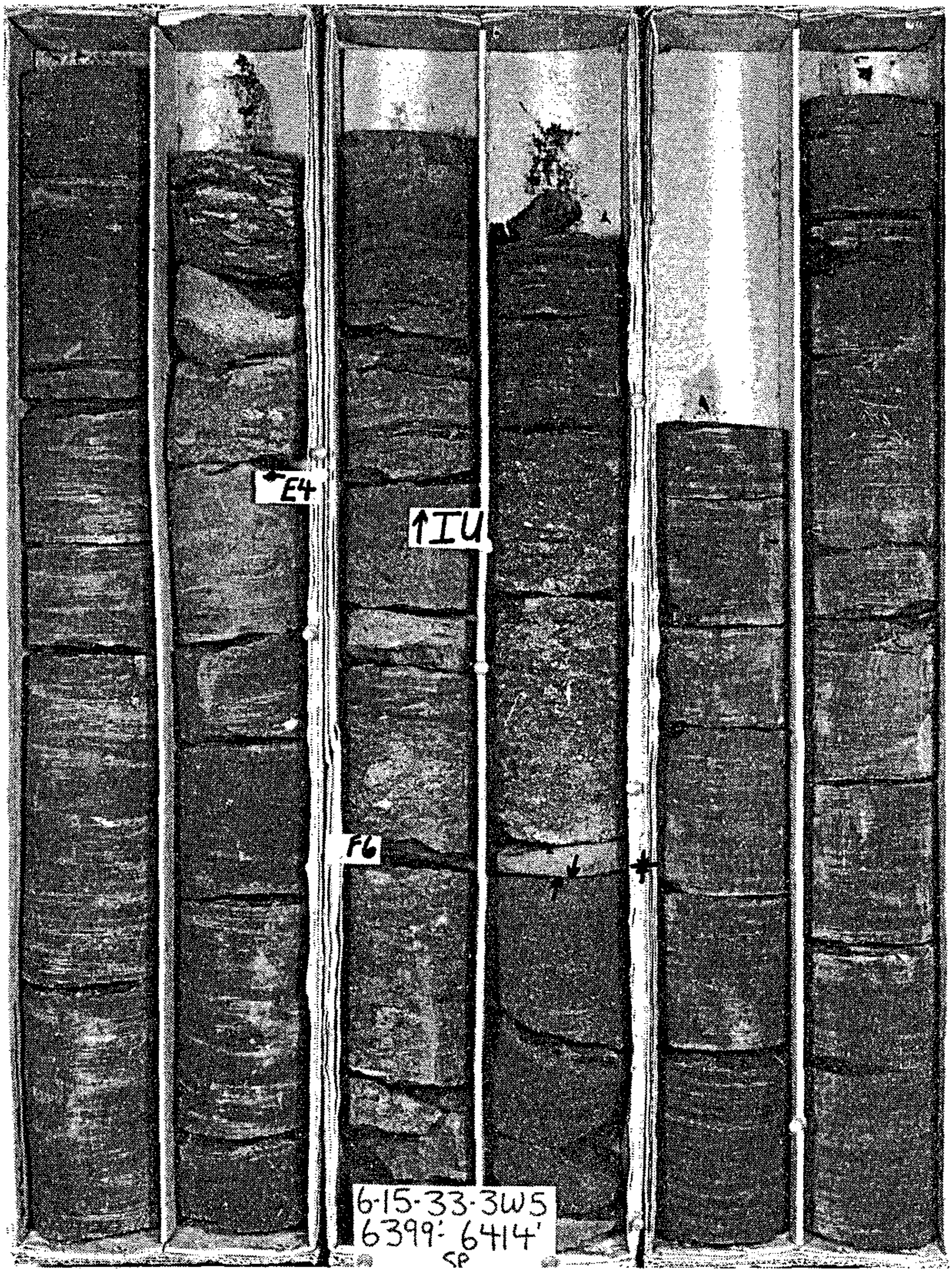

CAROLINE
CROSSFIELD
GARRINGTON
LOCHEND
Meters
0
1
2
3
4
I
IP
6P
8
7
6-7B-GS
6
IA/2A

Figure 3.11. An incomplete Burnstick Member vertical facies sequence from 6-15-33-3W5 in Garrington, consisting of facies 6 and facies 6-7B-GS (labelled as IU). The entire Burnstick Member facies sequence and the lower Raven River Member facies sequence is 1.61 meters thick. The stratigraphic top is towards the upper right.

The Burnstick Member begins in the second core sleeve at E4 and continues through to the contact with the Raven River Member in the lower third of the fourth core sleeve. The top of the LRRM sequence is near the base of the fifth core sleeve and is defined by the last occurrence of grit in facies 1P. If full each core sleeve would be approximately 75 cm long.


E4
↑IU
F6
6-15-33-3W5
6399'-6414'
SP

base (facies 6P) to a massive dark mudstone at the top (facies 1). Both the lower and upper contacts of the LRRM sequence are gradational, as are the contacts between the three facies in the sequence.

Some of the LRRM sequences do not exhibit the complete facies sequence from facies 6P into facies 1. Incomplete facies sequences are characterized by sharp basal contacts with the Burnstick Member and usually consist of facies 1P and facies 1.

The LRRM sequence is relatively thin compared to the BM sequence. The average thickness of the LRRM sequence in the four fields is 0.58 meters, while the average thickness of the BM sequence is 2.69 meters.

Off-Field Vertical Facies Sequences

In contrast to the two vertical facies sequences observed in the on-field areas, the vertical facies sequence observed in the off-field area is very thin (Figure 3.12). The off-field occurrence of the coarse sediment package is restricted to an area a few kilometers from the field boundaries. Due to the lack of cored off-field wells (15 out of 189) it is difficult to accurately map the extent of the off-field facies distributions. Some of the off-field cores do not contain a coarse sediment package, which suggests that the off-field facies are not laterally continuous between the fields.

Figure 3.12. A relatively thick "off-field" vertical facies sequence from 10-11-35-8W5 located approximately 7 kilometers to the west of Caroline. This core covers an interval from 8530 to 8545 feet. It is probable that this sequence is a northerly equivalent of the on-field Burnstick Member sediments of Lochend and is, therefore, not a true off-field facies sequence.

The base of the Burnstick Member (E4) is located in the upper part of the second core sleeve, while the top of the Burnstick Member is located in the upper part of the fourth core sleeve. Each core sleeve is approximately 75 cm long.


E4
F1A
Pebbly
F6
F1
F1P
10-11-35-8W5
8530'-8545'
SP

Based on the resistivity well log responses, the off-field coarse sediment package is best developed within five kilometers of the western field boundaries. This is consistent for all of the four fields in the study area.

The off-field vertical facies sequence consists of two facies: facies 1B and facies 1P. Facies 1B is observed at a stratigraphic interval that is at the same horizon as the on-field BM sequence, while facies 1P occurs at a stratigraphic interval that is at the same horizon as the on-field LRRM sequence. The lower and upper contacts of the off-field vertical facies sequence with facies 1A and facies 1 are both gradational, as is the contact between facies 1B and facies 1P. The maximum thickness of the facies 1B/facies 1P coarse sediment package is 0.75 meters.

3.4 Contacts

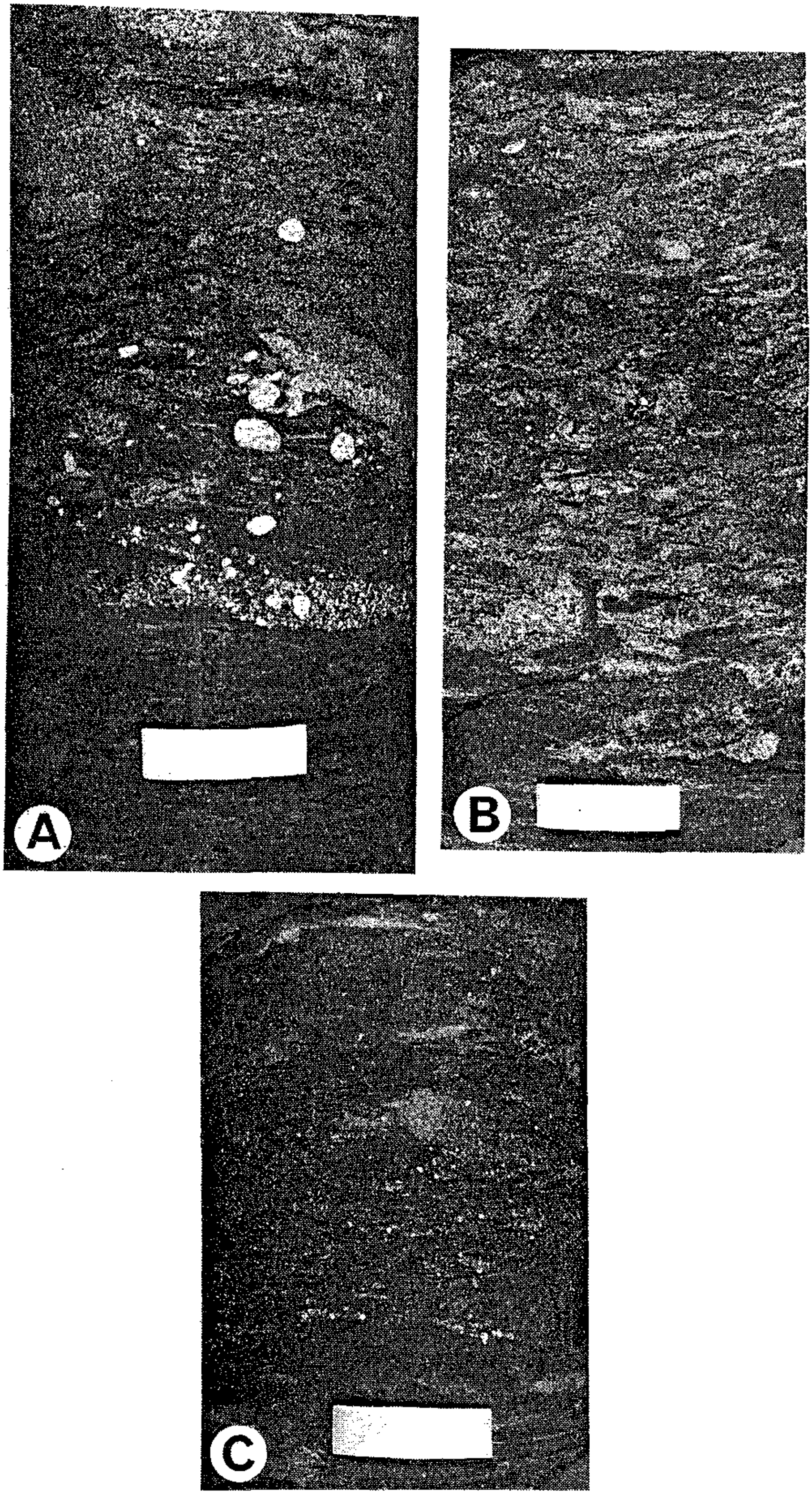
There are two contacts that separate the facies sequences of the Hornbeck Member, the Burnstick Member and the Raven River Member. The lower contact, between the Hornbeck Member and the base of the Burnstick Member, is defined by the change from facies 1A or facies 2A into facies 6. The upper contact, between the top of the Burnstick Member and the base of the Raven River Member, is defined by the change from facies 7 or facies 8 into facies 6P. Both the lower and the upper contacts can be relatively sharp which is in contrast to the gradational contacts observed between the other facies.

Defining a contact as being sharp or gradational is based on a comparison of the grain sizes in the facies above and below the contact, and the degree of mixing between the facies above and below the contact. For the lower contact a few scattered sand grains mixed into a background facies 1A would represent a gradational contact, while an abrupt occurrence of granules and pebbles above a facies 1A would represent a sharp contact. For the upper contact, a gradual transition from pebbly sandstone (facies 7) to a pebbly mudstone (facies 6P) would represent a gradational contact, while an abrupt transition from a pebbly sandstone to a massive dark mudstone (facies 1) would represent a sharp contact.

Defining a contact as being sharp or gradational is arbritary as there is a complete spectrum of contacts between the end members discussed above. Most contacts are defined by comparing the coarsest grain sizes within 20 cm of the contact (>4ϕ difference in grain size across the contact is considered sharp) and on the transitional thickness between the facies (<20 cm of mixing is considered sharp).

The lower contact between the Hornbeck Member and the Burnstick Member is usually quite sharp (Figures 3.13A and 3.13B). The sharpness of this contact can be highlighted by the occurrence of granules, pebbles and mud clasts at the base of facies 6, which is in sharp contrast to the dark

Figure 3.13. (A). Sharp contact between the Hornbeck Member and the Burnstick Member in 8-14-31-4W5 (Crossfield) at 7117 feet. (B). Sharp Hornbeck Member/Burnstick Member contact in 6-28-33-3W5 (Garrington) at 6381 feet. (C). A gradational Hornbeck Member/Burnstick Member contact from 10-9-32-2W5 (Garrington) at 6110 feet.


A
B
C

silty mudstone below. Pebbles up to 15 mm in diameter are commonly observed at this contact.

In some cores the contact between the two facies is gradational (Figure 3.13C). This could be due to either the extensive bioturbation of the coarse clasts into the mudstone, or the lack of coarse sediment supply in the facies near the contact. If one of these two conditions prevail, the resulting contact is diffuse or blurry (Figure 3.13C).

The sharpest contacts between the Hornbeck Member and the Burnstick Member occur in the Caroline and Crossfield sediments (Figure 3.14). Every one of the 28 lower contacts observed in the Caroline cores is defined as a sharp contact, while 32 out of 38 lower contacts in Crossfield sediments are defined as sharp.

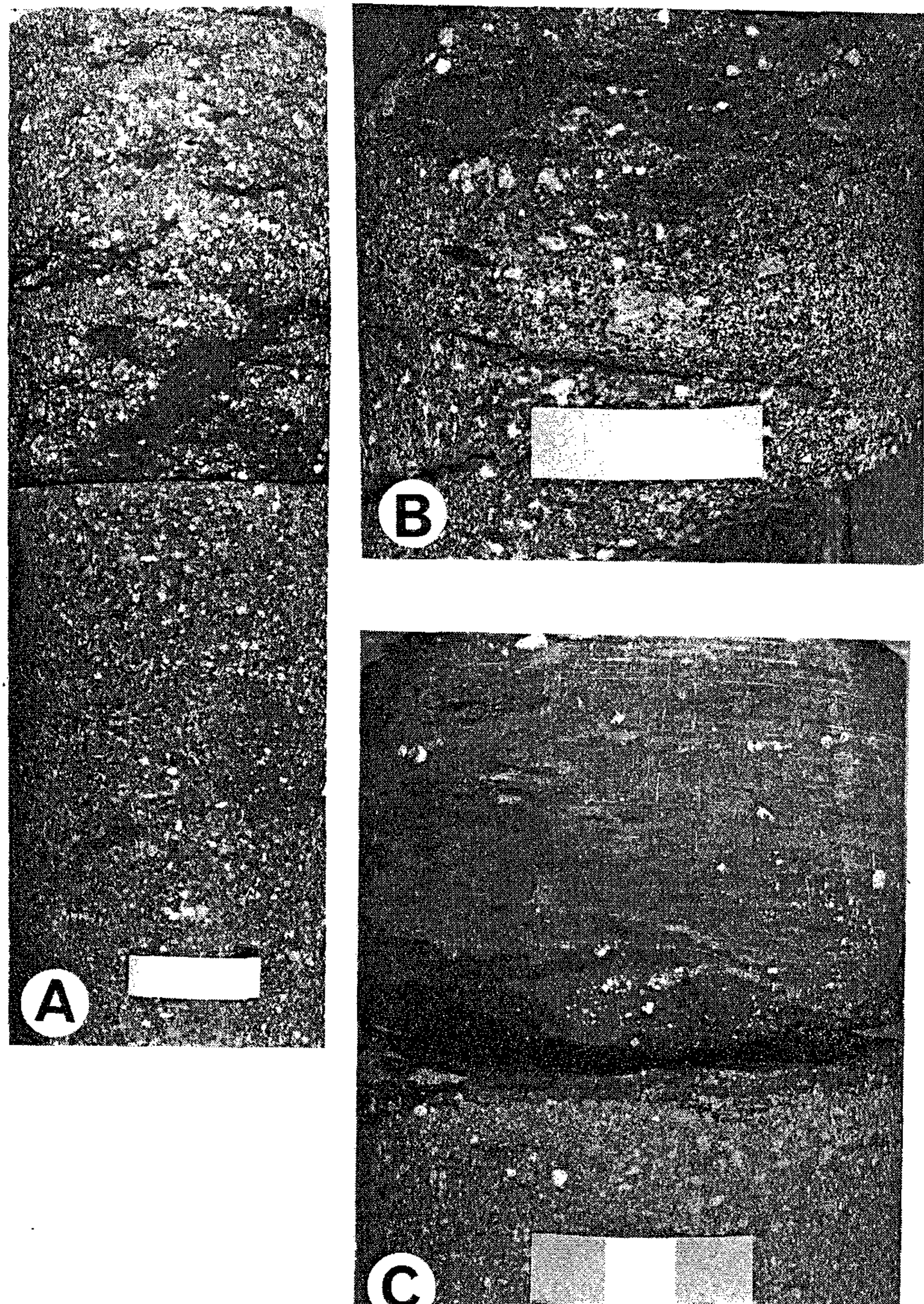
In contrast to the observations in Caroline and Crossfield, the lower contacts in Garrington and Lochend sediments are not as sharp. Only 36 of 61 lower contacts in Garrington are considered sharp, while 9 out of 13 contacts in Lochend are defined as sharp.

The upper contact between the Burnstick Member and the Raven River Member is gradational compared to the lower contact (Figures 3.15A and 3.15B). This contact is defined by the transition from facies 7 or facies 8 into facies 6P above. The sediments below the contact consist of a pebbly sandstone or a sandy conglomerate with a sandstone matrix, while the sediments above the contact consist of a sandy to a pebbly mudstone with a mudstone matrix. The change in

Field	# of Cores	Sharp	Gradational	Sharpness Index
Caroline	28	28	0	2.00
Crossfield	38	32	6	1.84
Garrington	61	36	25	1.59
Lochend	13	9	4	1.69

Figure 3.14. The sharpness of the Hornbeck Member/Burnstick Member contact for the four fields. The sharpness index is calculated by rating gradational contacts as 1, and sharp contacts as 2. The sharpness index then equals n(grad) X 1 + m(sharp) X 2 divided by the number of cores (n + m). Note the difference between the sharpness index of Caroline and the sharpness index of Garrington.

Figure 3.15. (A). A gradational Burnstick Member/Raven River Member contact from 6-10-30-3W5 (Crossfield) at 6784 feet. The contact occurs halfway up the core. (B). A gradational Burnstick Member/Raven River Member contact from 16-31-35-7W5 (Caroline) at 8434 feet. (C). A sharp Burnstick Member/Raven River Member contact from 10-8-36-5W5 (Garrington) at 6928 feet.


A
B
C

matrix from sandstone to mudstone marks the contact between the Burnstick Member and the Raven River Member.

The upper contact can be extremely sharp (Figure 3.15C) or it can be very gradational (Figures 3.15A and 3.15B). Most of the upper contacts in the study area are gradational, as shown by the tabulation of the upper contact data from the four fields (Figure 3.16). Only 29 of the 132 upper contacts in the study area were defined as sharp. This is in contrast to the sharpness of the lower contacts as 105 out of 140 lower contacts are defined as sharp (Figure 3.14).

Field	# of Cores	Sharp	Gradational	Sharpness Index
Caroline	23	3	20	1.13
Crossfield	42	8	34	1.19
Garrington	55	18	37	1.33
Lochend	12	0	12	1.00

Figure 3.16. The sharpness of the Burnstick Member/Raven River Member contacts for the four fields. Most of these contacts are gradational and the sharpness indicies for the fields are close to 1.00. Compare to the results in Figure 3.14.

CHAPTER 4: Cross Sections Across The Fields

4.1 Introduction

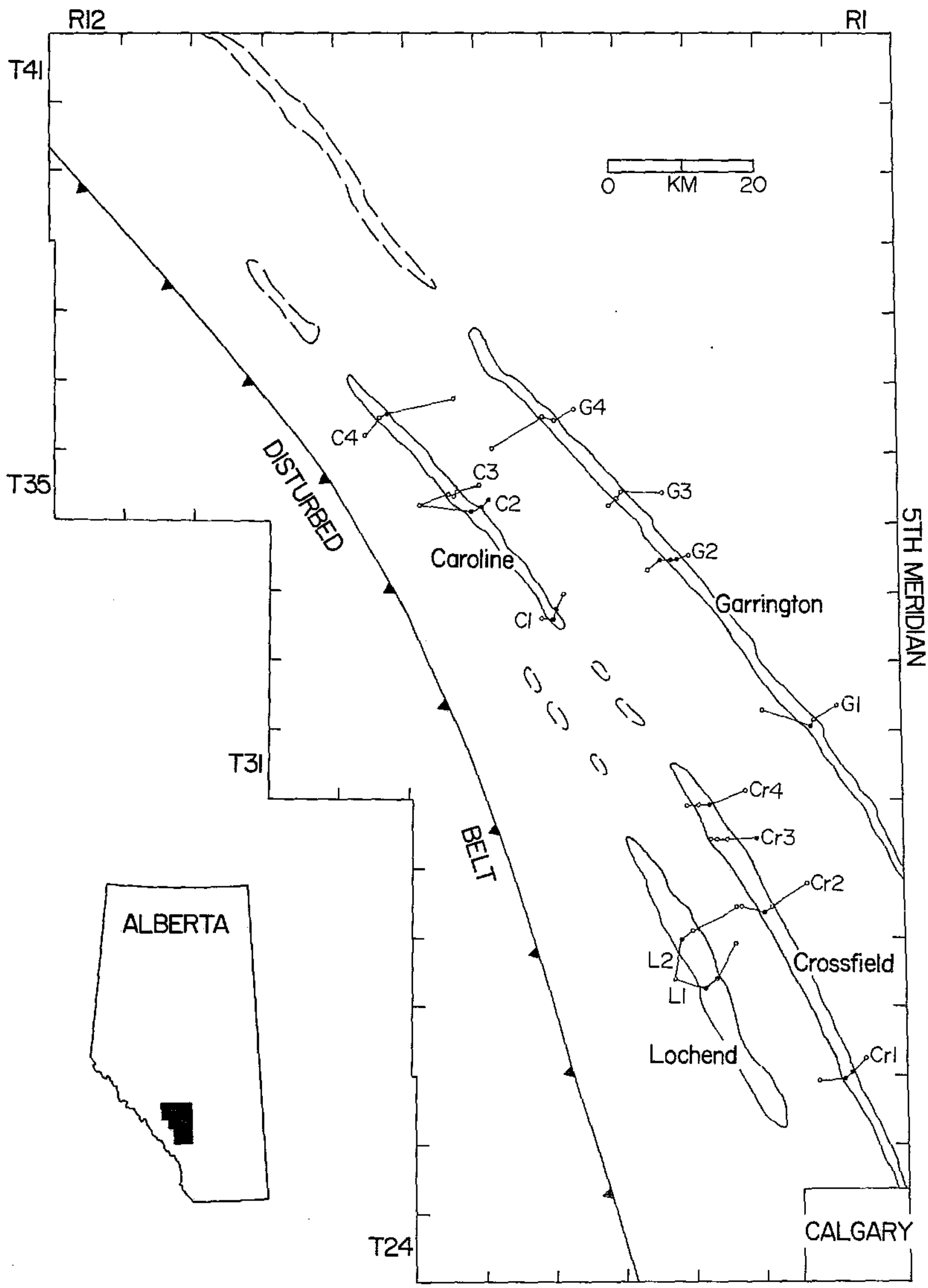
In order to understand the lateral facies changes and the two dimensional geometry of the Burnstick Member it is necessary to construct various cross sections across the four Burnstick Member fields. These fields are extremely narrow, which makes it difficult to construct long cross sections across the width of the fields. For this reason, most of the cross sections are between 3 to 5 km long and consist of two to five well logs or cores.

Fourteen well log cross sections and nine core cross sections have been constructed perpendicular to the strike of the fields, while two core cross sections have been constructed parallel to the strike of the fields.

4.2 Well Log Cross Sections

The purpose of the well log cross sections (Figure 4.1) is to reveal the two-dimensional sandstone geometry of the Burnstick Member perpendicular to the field strike. Of the fourteen well log cross sections, four are from each of Caroline, Crossfield and Garrington, while two are from Lochend.

Figure 4.1. Location map for the 14 well log cross sections that are oriented perpendicular to the strike of the fields. Solid circles represent cored wells, while open circles represent uncored wells.



R12
R1
T41
T35
T31
T24
0
KM
20
DISTURBED
BELT
C4
C3
C2
C1
Caroline
G4
G3
G2
G1
Garrington
5TH MERIDIAN
Cr4
Cr3
Cr2
Cr1
Crossfield
L2
L1
Lochend
CALGARY
ALBERTA

The sections contain four or five shallow focus resistivity well logs that penetrate the Burnstick Member. The outer two resistivity well logs, to the west and to the east of the fields, are located in off-field positions, while the inner resistivity well logs (two or three) are located in on-field positions. The inclusion of off-field well logs and on-field well logs into the cross sections allows for a complete correlation across the fields.

Four different horizons are consistently picked as markers on the resistivity well logs. These include an upper marker (UM), the top of the Burnstick Member (TB), the base of the Burnstick Member (BB) and a lower marker (LM).

The upper marker is defined as an inflection point on the resistivity well log that consistently occurs 2 to 20 m above the Burnstick Member. It is a very prominent marker and is easily traced across or between the fields.

The top and the base of the Burnstick Member are defined by prominent rightward deflections of the resistivity well logs producing a "blocky" type response in the on-field positions. Both the base of the Burnstick Member (BB) and the top of the Burnstick Member (TB) are easy to identify in the on-field positions, but become more difficult to identify in the off-field positions. Most of the off-field TB and BB markers merge together to produce a small spike that is labelled as the E4/T4 horizon.

The lower marker (LM) is observed below the Burnstick Member and is used as the datum for the fourteen well log cross sections. The lower marker is identified as a small rightwards deflection on the resistivity well log and is traceable across or between the four fields. Some difficulties were encountered in correlating the lower marker between the four fields, as the log signature changes slightly between the fields. This difficulty was overcome by tracing and overlaying the resistivity well logs, thus comparing both the overall log shape and the position of the distinct log spikes, until a confident correlation could be made.

The lower marker was chosen as the datum for the cross sections because it provides a "close up" view of the two-dimensional geometry of the Burnstick Member. It was important to identify a lower marker close to the base of the Burnstick Member due to the thinness of the Burnstick Member. If a deeper marker had been chosen as the datum, it would tend to mask the geometry of the Burnstick Member, while an upper marker might drape any topography developed on top of the Burnstick Member. Using the lower marker as the datum allows for an interpretation of the basinal topography before and after the deposition of the Burnstick Member sediments.

In the following discussion, the fourteen well log cross sections will be discussed field by field beginning with the well log cross sections from Caroline.

Caroline

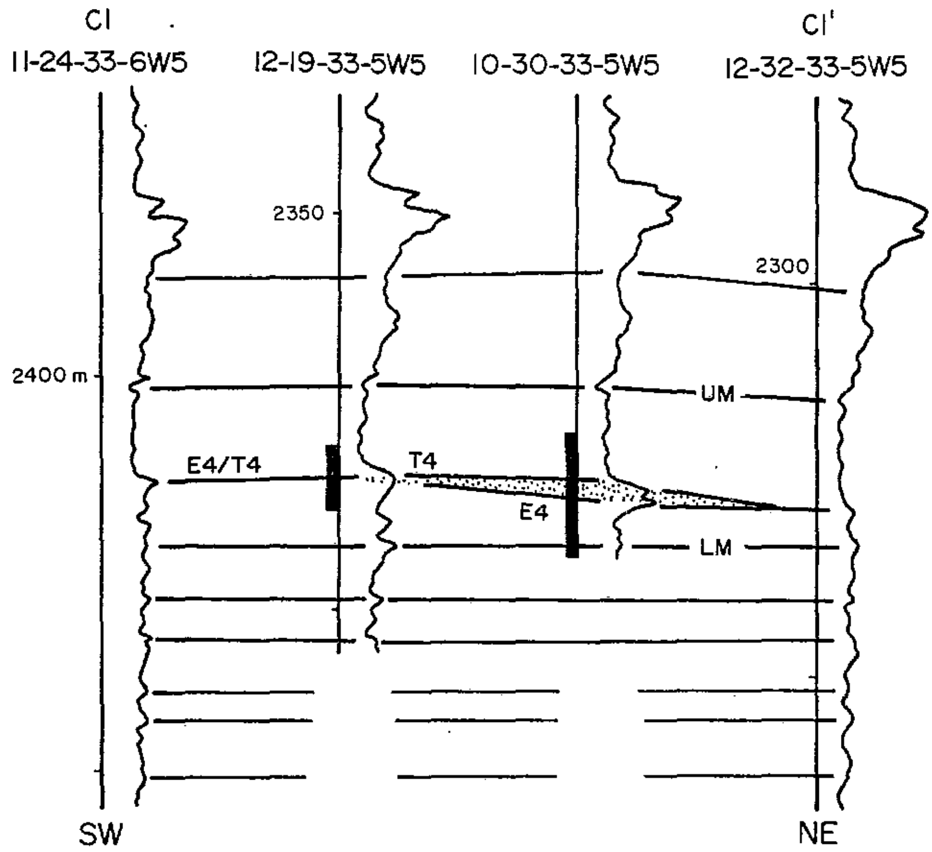
There are four well log cross sections from Caroline: C1, C2, C3 and C4 (Figures 4.2 and 4.3). Of the 17 resistivity well logs used for the cross sections, 9 are from on-field positions while the other 8 are from off-field positions.

Some of the similiarities observed between the four well log cross sections include: (1) the thickness of the UM-LM stratigraphic interval, (2) the UM and LM markers are almost parallel, (3) the rapid thickening of the Burnstick Member from the off-field to the on-field positions, (4) the drop of the base of the Burnstick Member from the west to east across the field and, (5) the slight convex upward nature of the top of the Burnstick Member.

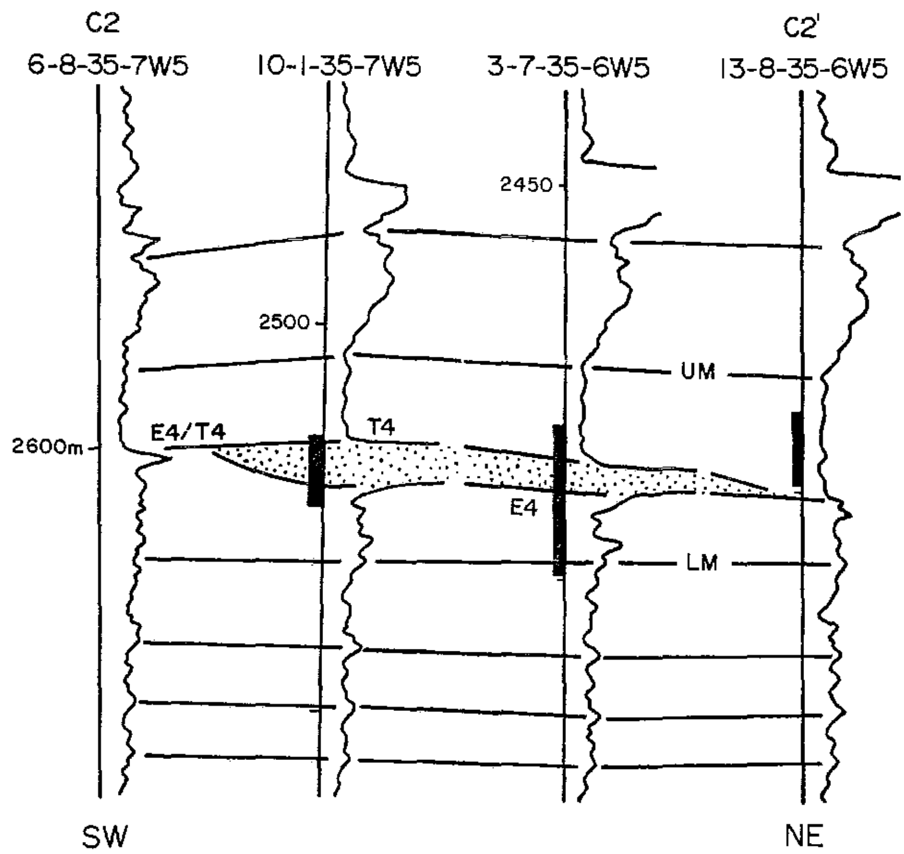
The maximum thickness of the Burnstick Member occurs in 10-01-35-7W5 (C2) where it reaches 6.7 meters thick (Figure 4.2). Most of the other on-field wells have Burnstick Member thicknesses between 0.8 - 5.8 m. Both the base and the top of the Burnstick Member appear to have sharp contacts with the surrounding sediments.

The off-field well logs have very subdued Burnstick Member signatures compared to the on-field well log signatures. The western off-field signature (E4/T4) is located at a stratigraphic interval equivalent to the on-field top of the Burnstick Member, while the eastern off-field signature (E4/T4) is at a stratigraphic interval equivalent to the on-

Figure 4.2. Two well log cross sections from Caroline, located in Figure 4.1. The markers are correlated, and E4/T4 is lettered. The Burnstick Member is contained between E4 and T4 where the resistivity markers deflect sharply to the right. The upper marker (UM) and the lower marker (LM) are also labelled.

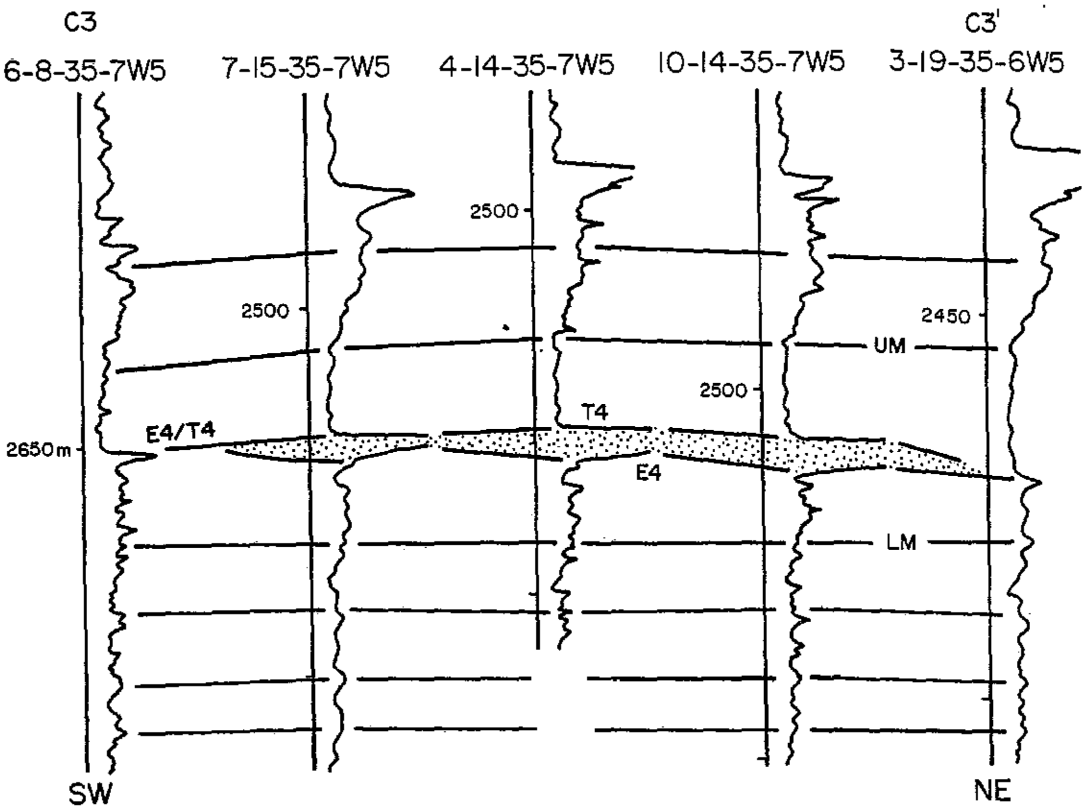


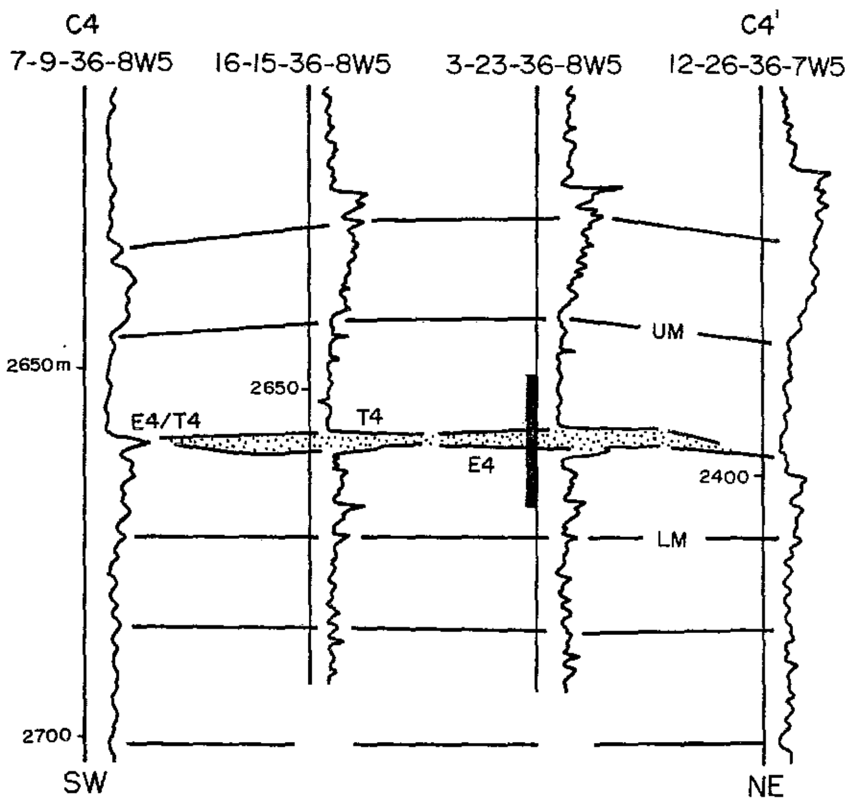
CI
11-24-33-6W5
12-19-33-5W5
10-30-33-5W5
CI'
12-32-33-5W5
2350
2300
2400 m
UM
E4/T4
T4
E4
LM
SW
NE



C2
6-8-35-7W5
10-1-35-7W5
3-7-35-6W5
C2'
13-8-35-6W5
2450
2500
UM
E4/T4
T4
2600m
E4
LM
SW
NE

Figure 4.3. Well log cross sections C3 and C4 from Caroline, located in Figure 4.1. The markers are correlated and E4/T4 is lettered. The Burnstick Member is located between E4 and T4, and is bracketed in between the upper marker (UM) and the lower marker (LM).


C3
C3'
6-8-35-7W5
7-15-35-7W5
4-14-35-7W5
10-14-35-7W5
3-19-35-6W5
2500
2500
2450
UM
2500
T4
E4/T4
2650m
E4
LM
SW
NE


C4
C4'
7-9-36-8W5
16-15-36-8W5
3-23-36-8W5
12-26-36-7W5
UM
2650m
2650
E4/T4
T4
E4
2400
LM
2700
SW
NE

field base of the Burnstick Member. Burnstick Member off-field to the west responses are much sharper than those to the east, especially in cross sections C2 and C4 (Figures 4.2 and 4.3).

Crossfield

There are four well log cross sections from Crossfield, Cr1, Cr2, Cr3 and Cr4 (Figures 4.4 and 4.5). Each of the four cross sections consists of two resistivity well logs from the off-field positions and two resistivity well logs from the on-field positions.

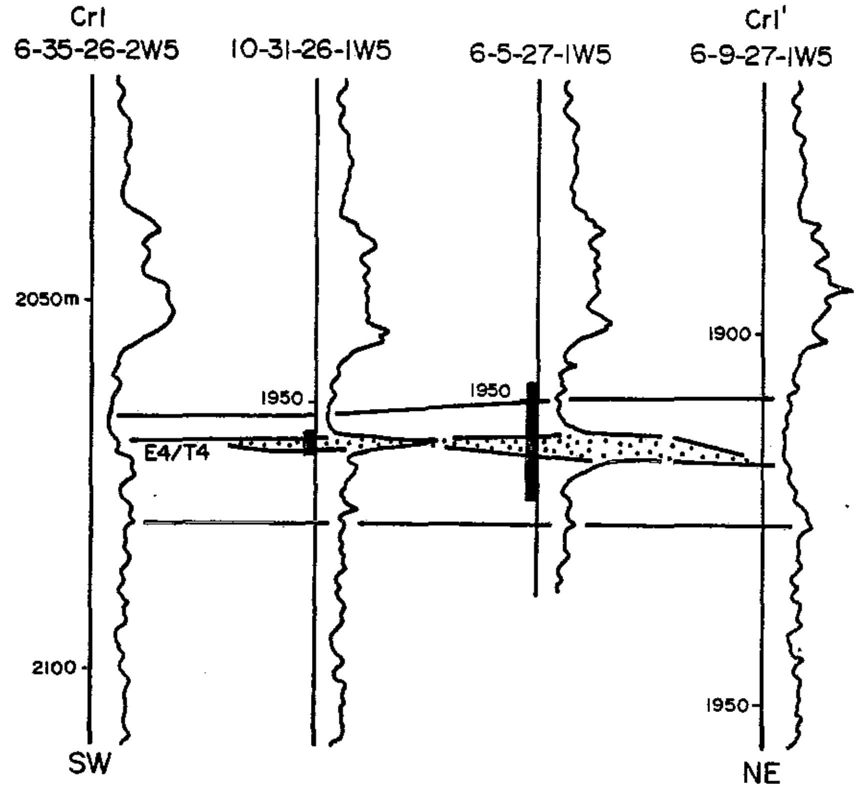
The Burnstick Member response off-field to the west rests stratigraphically higher than that to the east. This outlines a drop in the base of the Burnstick Member from west to east across Crossfield. A maximum drop of 6 meters from the off-field west to the off-field east Burnstick Member response is observed in cross sections Cr2 (Figure 4.4) and Cr4 (Figure 4.5).

The thickest occurrence of the Burnstick Member is observed in 10-18-29-2W5 (Cr2) where it reaches 6.8 meters thick. Most other on-field Burnstick Member responses are between 1.5 - 6.0 m thick.

The two-dimensional sandstone geometry of the Burnstick Member in the Crossfield well log cross sections resembles a sigmoidal or an S-shaped profile. This is especially observed in Cr2 and Cr4.

Figure 4.4. Well log cross sections Cr1 and Cr2 from Crossfield, located in Figure 4.1. The base of the Burnstick Member drops from the southwest to the northeast across both of the cross sections. Note the change in the lower marker signal in Cr1.

The Burnstick Member is shown by the dots and is bracketed by the lower marker and the upper marker.


Cr1
6-35-26-2W5
10-31-26-1W5
6-5-27-1W5
Cr1'
6-9-27-1W5
2050m
1950
1950
1900
E4/T4
2100
1950
SW
NE

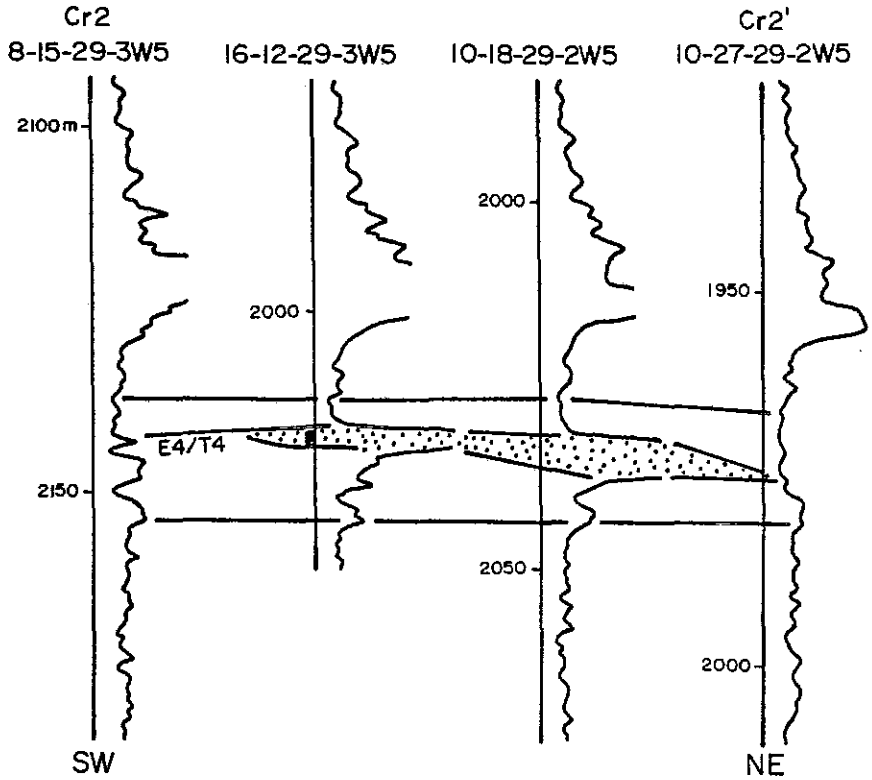
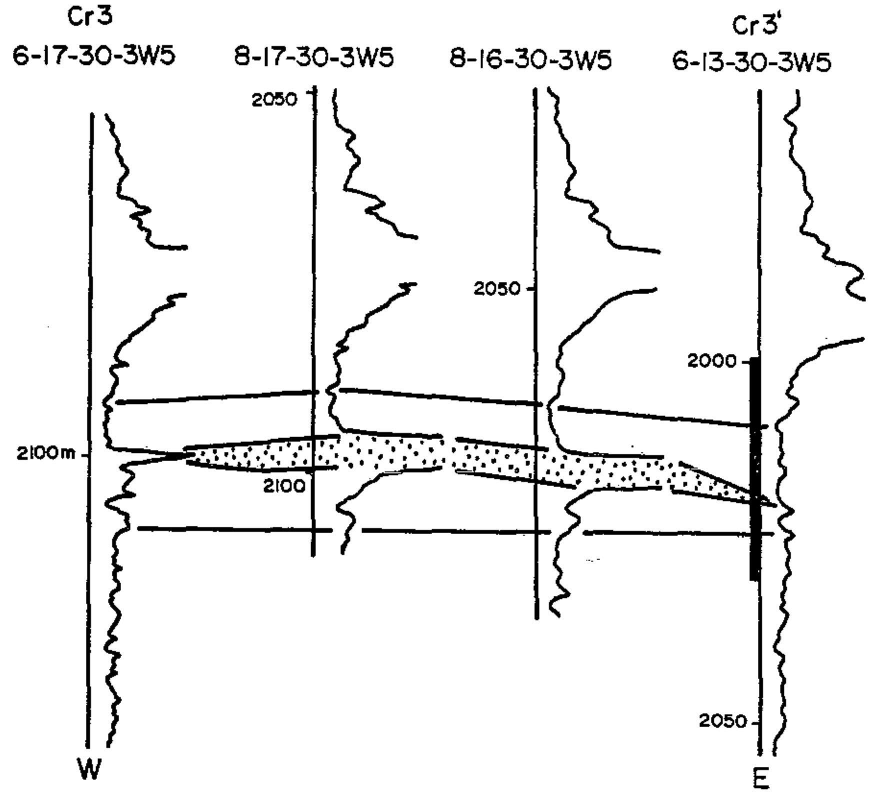
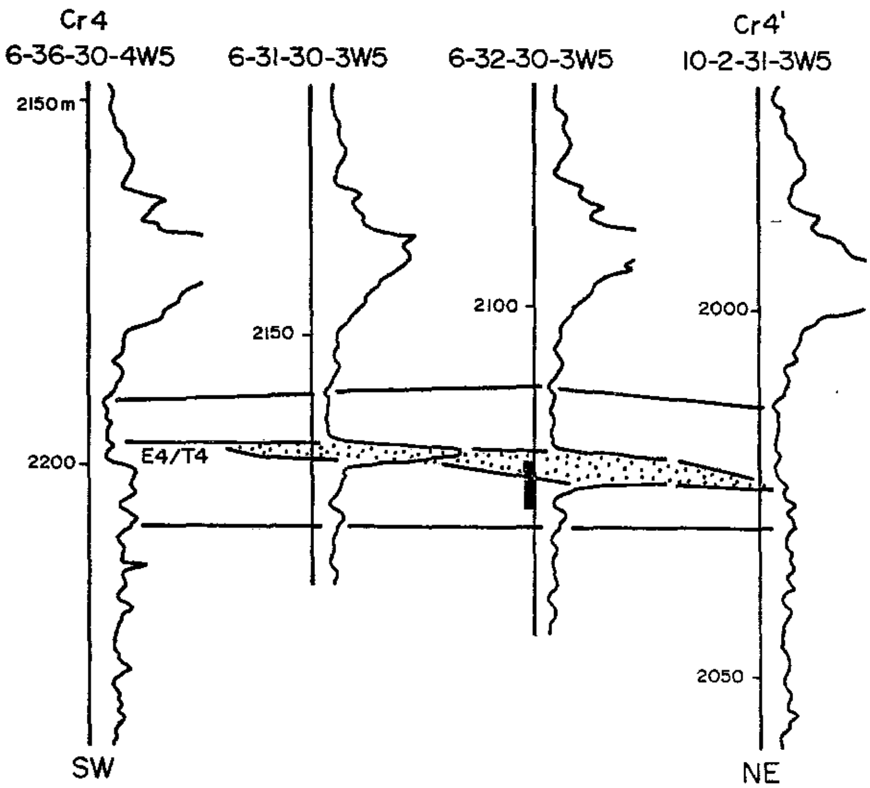

Cr2
8-15-29-3W5
16-12-29-3W5
10-18-29-2W5
Cr2'
10-27-29-2W5
2100m
2000
1950
2000
E4/T4
2150
2050
2000
SW
NE

Figure 4.5. Well log cross sections Cr3 and Cr4 from Crossfield, located in Figure 4.1. The Burnstick Member is shown with dots and is bracketed by a lower and an upper marker.


Cr3
6-17-30-3W5
8-17-30-3W5
8-16-30-3W5
Cr3'
6-13-30-3W5
2050
2050
2000
2100m
2100
2050
W
E


Cr4
6-36-30-4W5
6-31-30-3W5
6-32-30-3W5
Cr4'
10-2-31-3W5
2150m
2100
2000
2150
2200
E4/T4
2050
SW
NE

Garrington

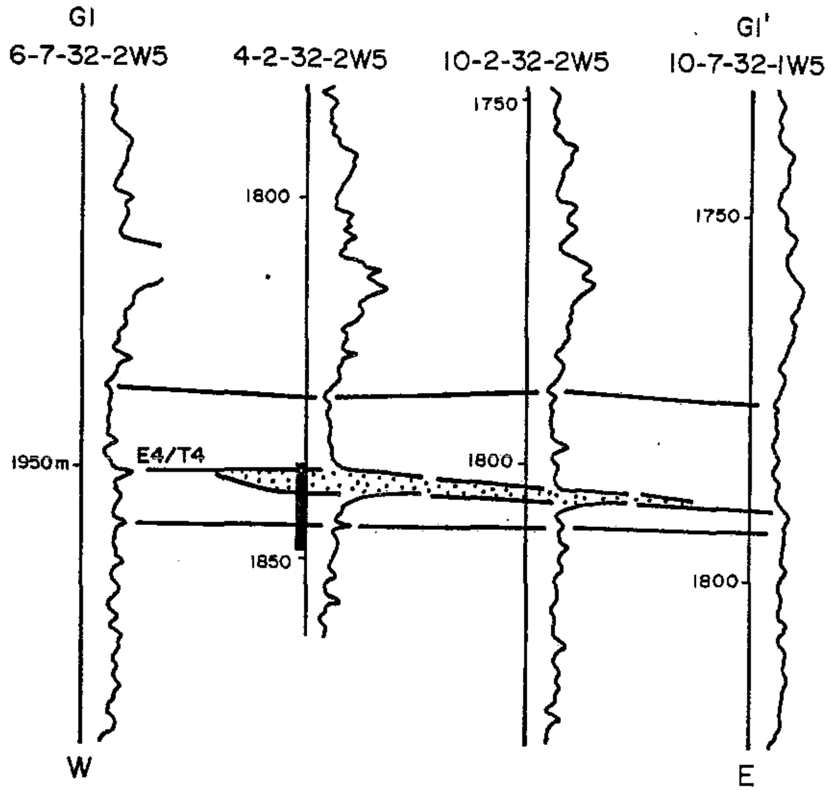
The four Garrington well log cross sections, G1, G2, G3 and G4, consist of 17 resistivity well logs, 9 of which are from on-field positions (Figures 4.6 and 4.7). These well log cross sections have many similarities with the well log cross sections from the other fields.

One of the diagnostic characteristics of the Garrington well log cross sections is the stratigraphic position of the off-field Burnstick Member responses. These responses rest stratigraphically higher on the west than on the east, defining a drop in the Burnstick Member across Garrington. The maximum drop across Garrington is 5.0 meters and is observed in cross section G3 (Figure 4.7).

Other characteristics of the Garrington well log cross sections include, (1) the S-shaped or sigmoidal two-dimensional geometry of the Burnstick Member, (2) the consistent thickness of the UM-LM stratigraphic interval, and (3) the rapid thickening of the Burnstick Member from the off-field to the on-field positions.

Two aspects of the Garrington well log cross sections distinguish them from the well log cross sections of the other fields. These are the thickness of the Burnstick Member and the thickness of the BB-LM stratigraphic interval. The Burnstick Member in Garrington is thinner than the Burnstick Member in the other fields and averages between 0.5 - 3.0 m. This contrasts with the average thickness of the

Figure 4.6. Well log cross sections G1 and G2 from Garrington, located in Figure 4.1. The Burnstick Member (dots) drops towards the lower marker from the west to the east.


G1
6-7-32-2W5
4-2-32-2W5
10-2-32-2W5
G1'
10-7-32-1W5
1750
1800
1750
1950m
E4/T4
1800
1850
1800
W
E

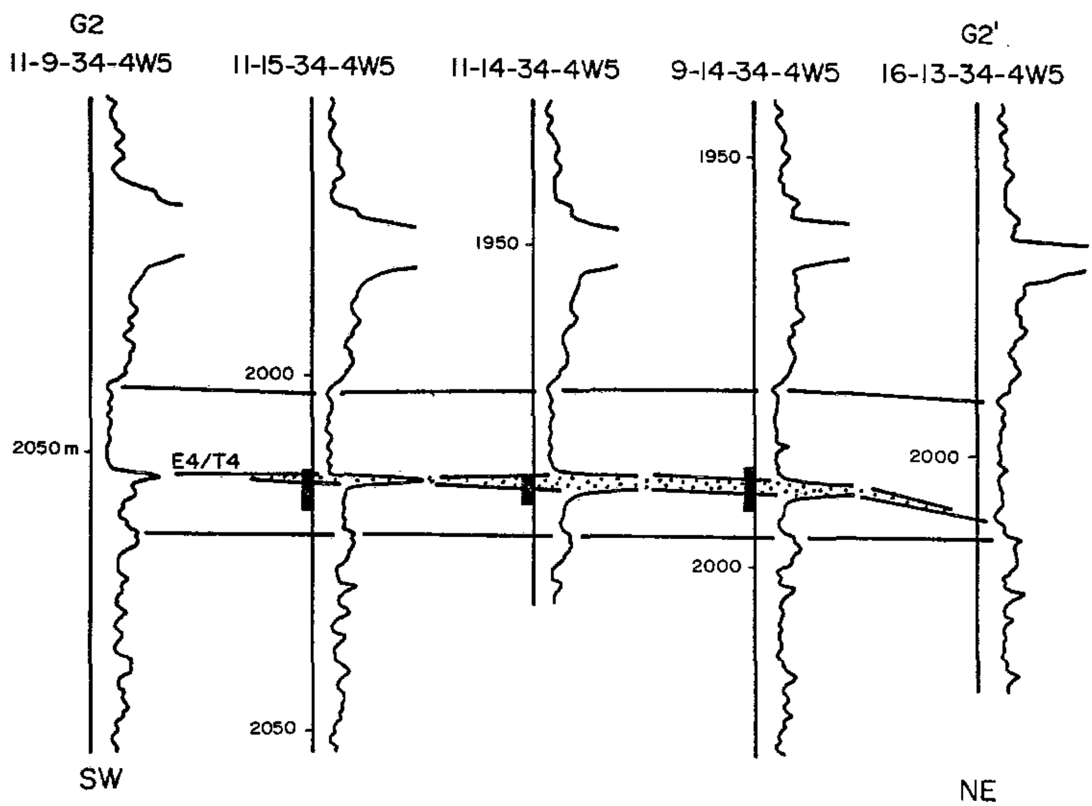
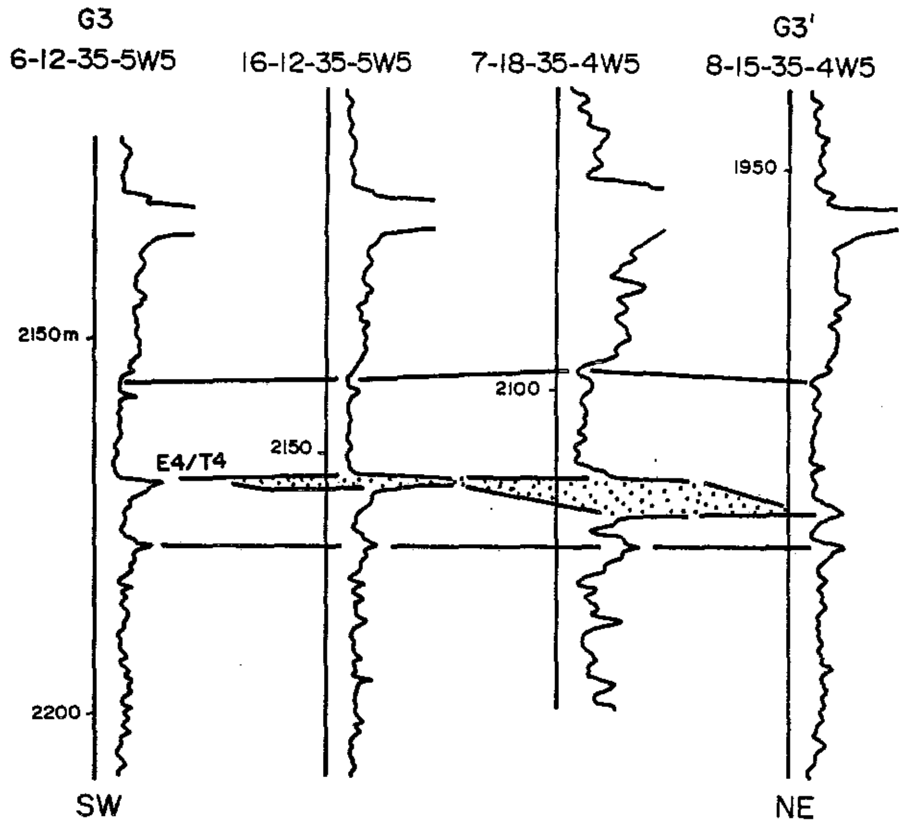
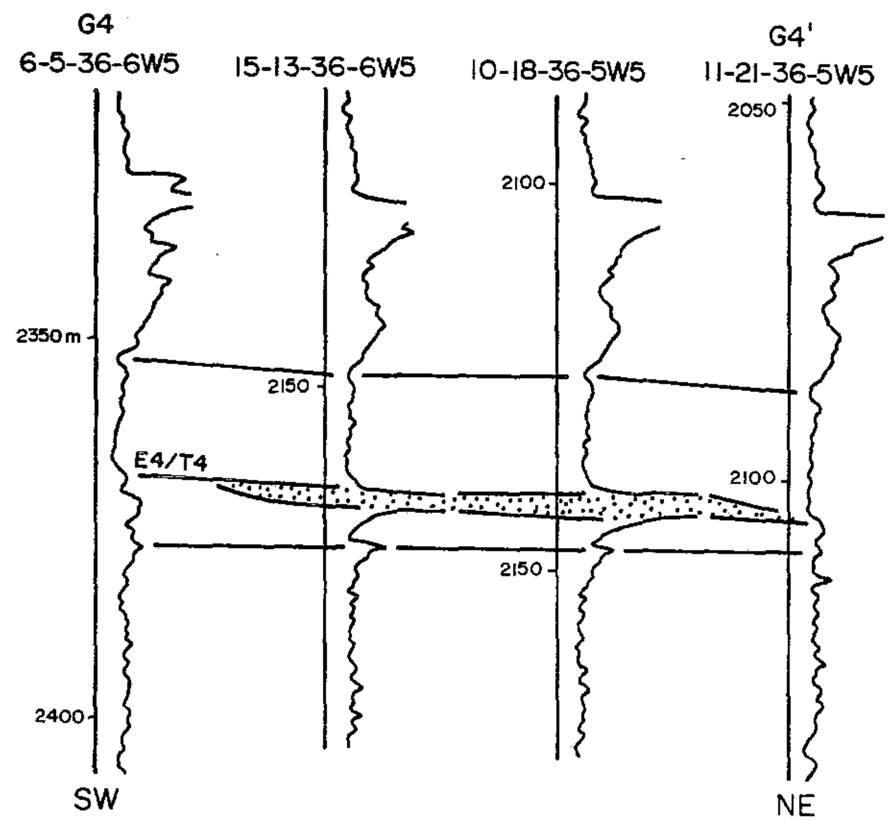

G2
11-9-34-4W5
11-15-34-4W5
11-14-34-4W5
9-14-34-4W5
G2'
16-13-34-4W5
1950
1950
2000
2050m
E4/T4
2000
2000
2050
SW
NE

Figure 4.7. Well log cross sections G3 and G4 from Garrington, located in Figure 4.1. The Burnstick Member is shown with dots and is bracketed by the lower and upper markers.


G3
6-12-35-5W5
16-12-35-5W5
7-18-35-4W5
G3'
8-15-35-4W5
1950
2150m
2100
2150
E4/T4
2200
SW
NE


G4
6-5-36-6W5
15-13-36-6W5
10-18-36-5W5
G4'
11-21-36-5W5
2050
2100
2350m
2150
E4/T4
2100
2150
2400
SW
NE

Burnstick Member in the other fields that is between 0.8-6.0 m thick. The BB-LM stratigraphic interval ia also relatively thin in the Garrington field as it usually is between 3.0 - 6.0 m thick. In contrast, the other fields usually have a BB-LM interval that is between 5.0 - 13.0 m thick.

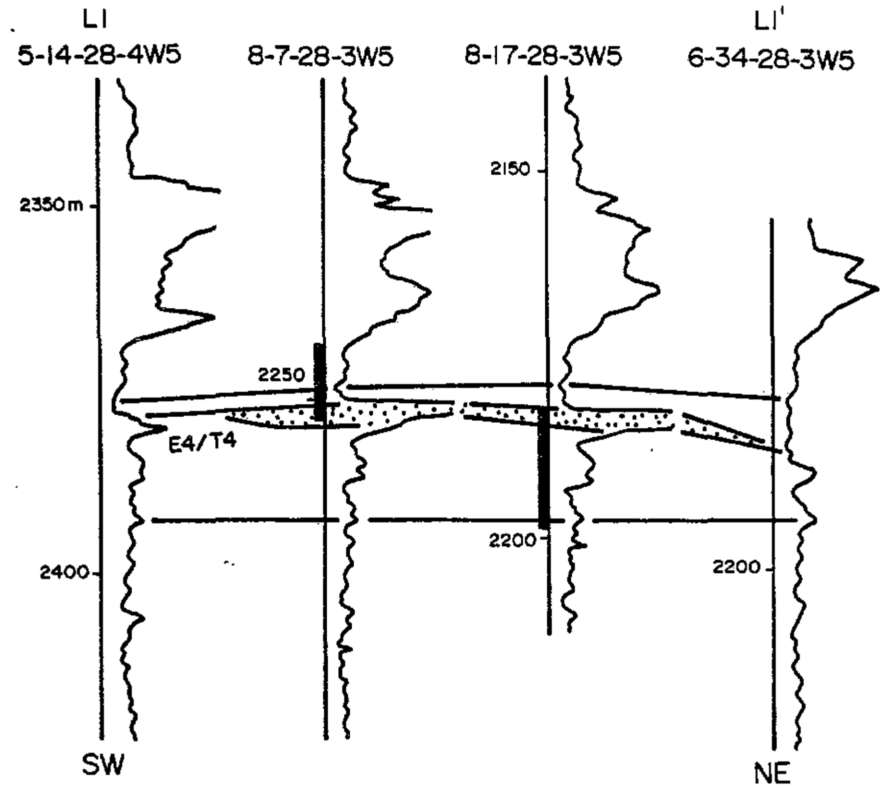
Lochend

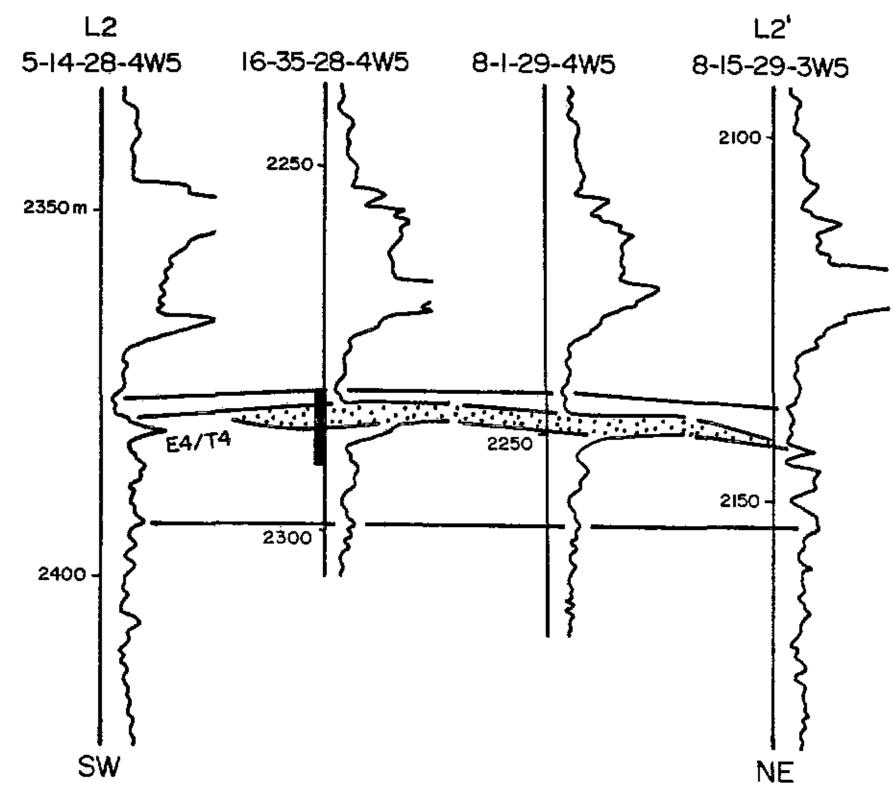
There are two well log cross sections from Lochend, L1 and L2, that consist of four resistivity well logs each (Figure 4.8). Two of the well logs are from off-field positions while the other two are from the on-field positions.

The thickness of the Burnstick Member in the Lochend well log cross sections varies from 3.4 to 3.9 m, while the BB-LM interval varies from 10.0 to 15.0 m. The two dimensional sandstone geometry of the Burnstick Member defines an S-shaped or sigmoidal surface that rests stratigraphically higher on the west than on the east.

The most significant difference between the Lochend well log cross sections and the well log cross sections from the other fields is the stratigraphic position of the Burnstick Member within the UM-LM interval. The Burnstick Member sediments in Lochend rest immediately below the upper marker (UM) and occupy the upper part of the UM-LM interval. This is in contrast to the occurrence of the Burnstick Member in

Figure 4.8. Well log cross sections L1 and L2 from Lochend, located in Figure 4.1. The Burnstick Member (dots) drops from the SW to the NE across L1 and L2.


L1
L1'
5-14-28-4W5
8-7-28-3W5
8-17-28-3W5
6-34-28-3W5
2350m
2150
2250
E4/T4
2200
2400
2200
SW
NE


L2
L2'
5-14-28-4W5
16-35-28-4W5
8-1-29-4W5
8-15-29-3W5
2100
2250
2350m
E4/T4
2250
2150
2300
2400
SW
NE

the lower to middle UM-LM stratigraphic interval in the other three fields.

4.3 Core Cross Sections

Seven different core cross sections were constructed perpendicular to the strike of the fields (Figure 4.9). The purpose of the core cross sections is to determine: (1) the lateral facies relationships of the Burnstick Member perpendicular to the strike of the field, (2) the two dimensional geometry of the Hornbeck Member/Burnstick Member contact, and, (3) the two dimensional geometry of the Burnstick Member/Raven River Member contact.

The longest core cross section is from Crossfield, consisting of three cores. Due to the narrow width of the fields it is impossible to construct core sections longer than four cores. Most of the cores are 1 to 3 km apart perpendicular to the strike of the fields.

All of the core cross sections are hung on the lower marker (LM) which is used as the datum. Of the seven core cross sections, six are from Caroline, Crossfield and Garrington (2 per field), while the other one is from Lochend. The legend for the seven core cross sections is located in Figure 4.10.

Figure 4.9. Location map for the seven core cross sections that are oriented perpendicular to the strike of the fields.

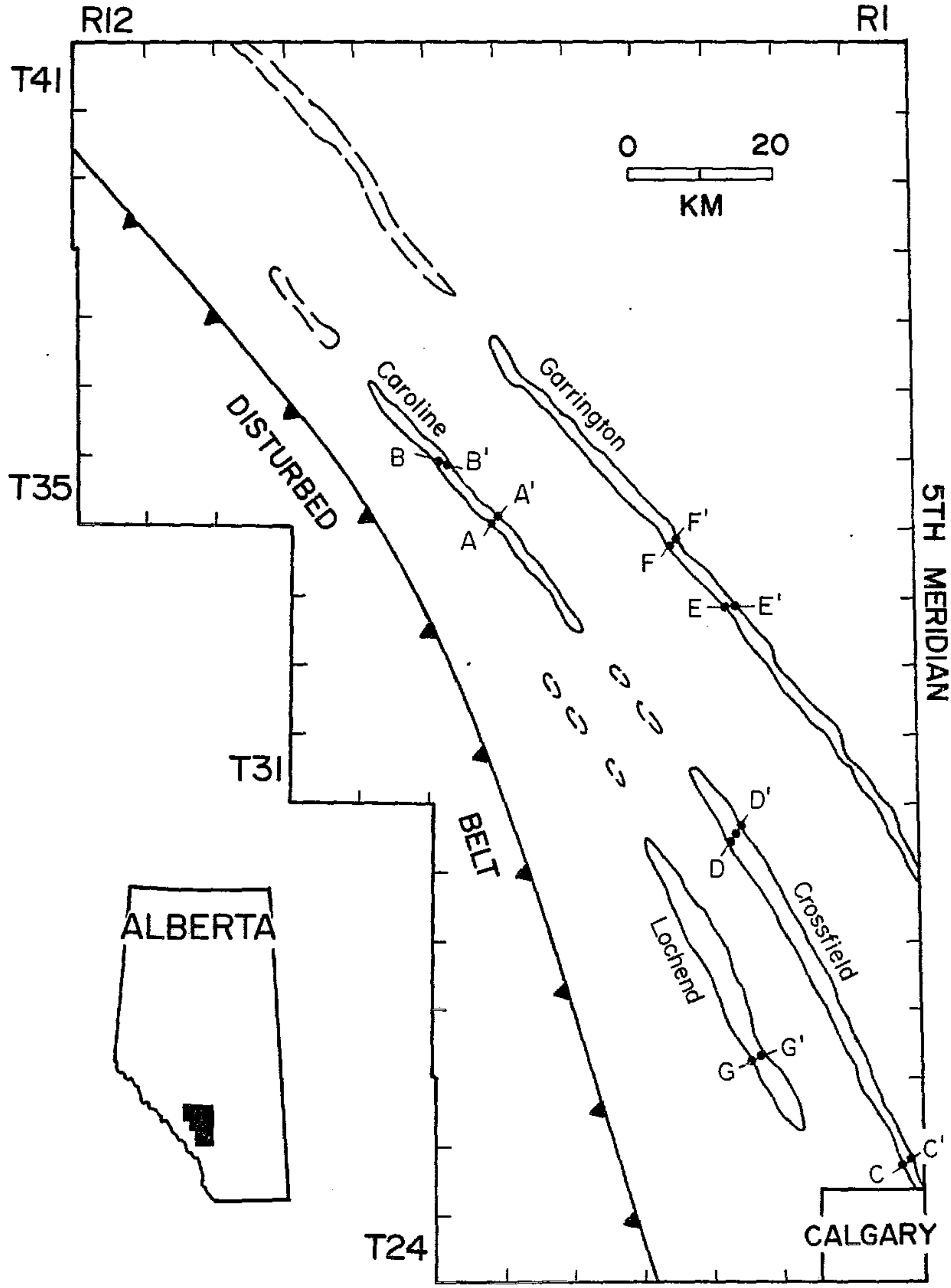
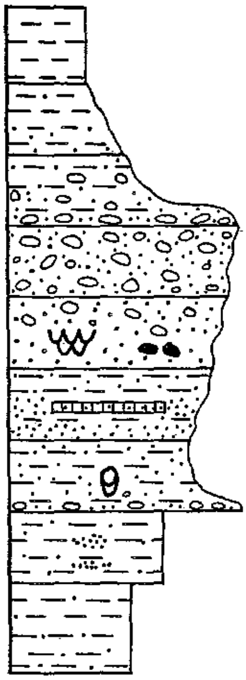

R12
R1
T41
T35
T31
T24
0
20
KM
DISTURBED
BELT
Caroline
Garrington
Crossfield
Lochend
5TH MERIDIAN
ALBERTA
CALGARY
A
A'
B
B'
C
C'
D
D'
E
E'
F
F'
G
G'

Figure 4.10. Legend for the core cross sections that shows the nine different facies and their corresponding characteristics. This legend should be used for all of the schematic facies diagrams in the thesis.



Facies I. Massive Dark Mudstone

Facies IP. Dark Mudstone with Scattered Grit

Facies 6P. Pebbly Dark Mudstone

Facies 8. Conglomerate

Facies 7. Non-bioturbated Sandstone

Facies 6-7B-GS. Interbedded Mudstone, Sandstone and Siderite

Facies 6. Speckled Gritty Mudstone

Facies 2A. Dark Silty Mudstone with Siltstone Beds

Facies IA. Dark Silty Mudstone

Mud Clasts

Coal Clasts

Bioturbation

Trough Cross Bedding

Gritty Siderite

T4 Burnstick Mb/Raven River Mb Contact

E4 Hornbeck Mb/Burnstick Mb Contact

Caroline

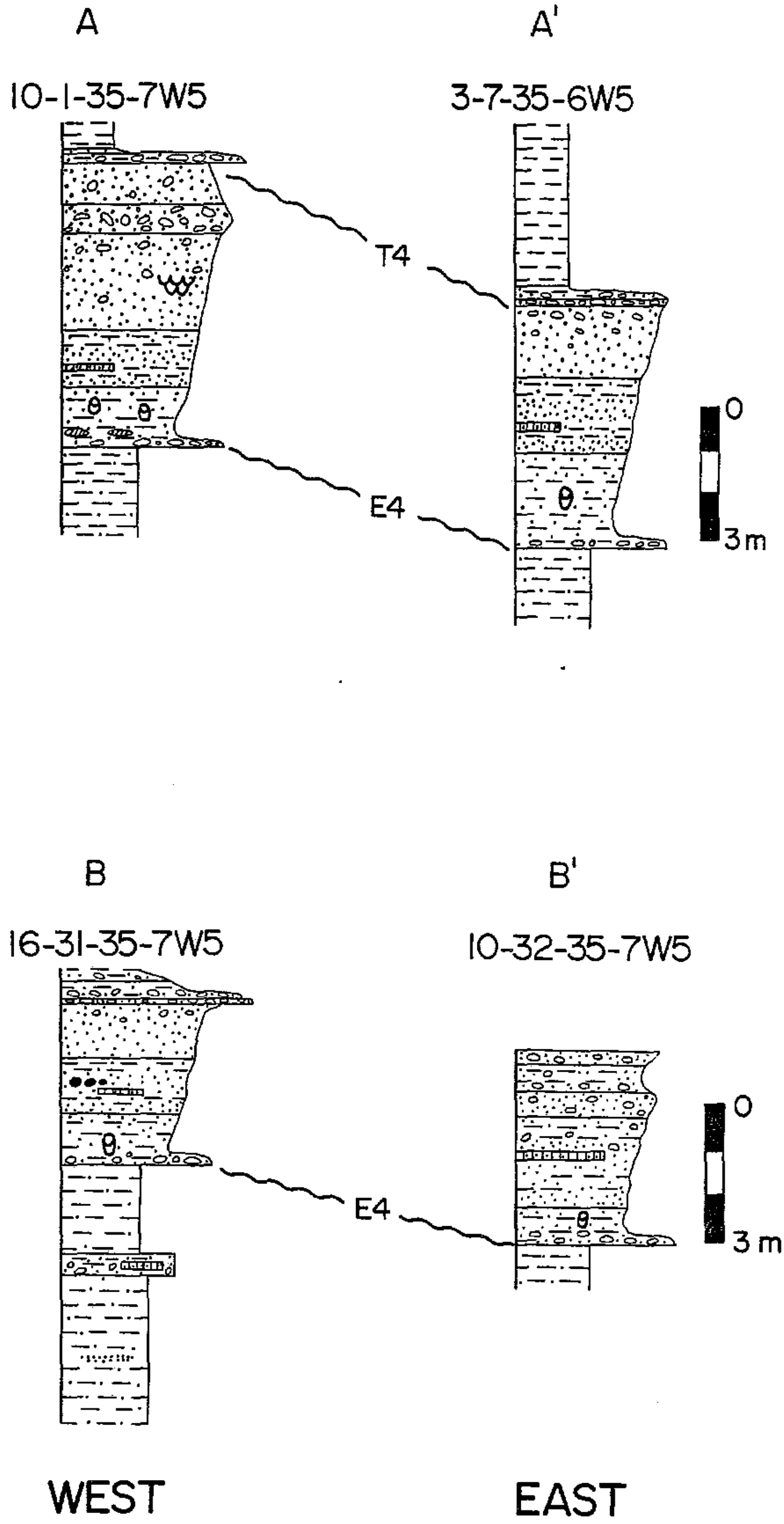
Cross section AA' consists of two cores from the central part of Caroline (Figure 4.11). Both cores exhibit a complete BM facies sequence and a complete LRRM facies sequence.

Facies 7 and facies 8 are best developed in 10-1-35-7W5 (3.7 meters) and tend to thin towards the northeast in 3-7-35-6W5 (1.9 meters). In contrast, facies 6 thickens from 1.3 meters in 10-1-35-7W5 to 2.2 meters in 3-7-35-6W5. Both of these observations suggest that the Burnstick Member in this area of Caroline becomes sandier towards the southwest and muddier towards the northeast.

The lower contact, between the Hornbeck Member and the Burnstick Member is extremely sharp in cross section AA'. Pebbles up to 10 mm in diameter are observed near the base of facies 6 in 10-1-35-7W5 along with 5 to 7 mm coal clasts. The two dimensional geometry of the lower contact (E4) defines a drop of approximately 2 meters from west to east. This drop is consistent with those observed in the Caroline well log cross sections.

The upper contact (Burnstick Member/Raven River Member), labelled as T4, is relatively sharp in 10-1-35-7W5 and is gradational in 3-7-35-6W5. Pebbles up to 11 mm in diameter are observed in the lower facies 6P of 10-1-35-7W5 and are in contrast to the granular sandstone of facies 7 below. The

Figure 4.11. Core cross sections AA' and BB' from Caroline, located in Figure 4.9. These core cross sections are hung on the lower marker (LM) and are constructed perpendicular to the strike of Caroline.


A
A'
10-1-35-7W5
3-7-35-6W5
T4
E4
0
3m
B
B'
16-31-35-7W5
10-32-35-7W5
E4
0
3 m
WEST
EAST

CAROLINE

upper contact (T4) also drops from west to east mirroring the geometry of the E4 surface below.

Cross section BB', the second core section across Caroline, also consists of two cores (Figure 4.11). This core section is located north of AA' and is oriented in a WNW-ESE direction. Complete BM and LRRM facies sequences are observed in 16-31-35-7W5, while only a complete BM facies sequence is observed in 10-32-35-7W5.

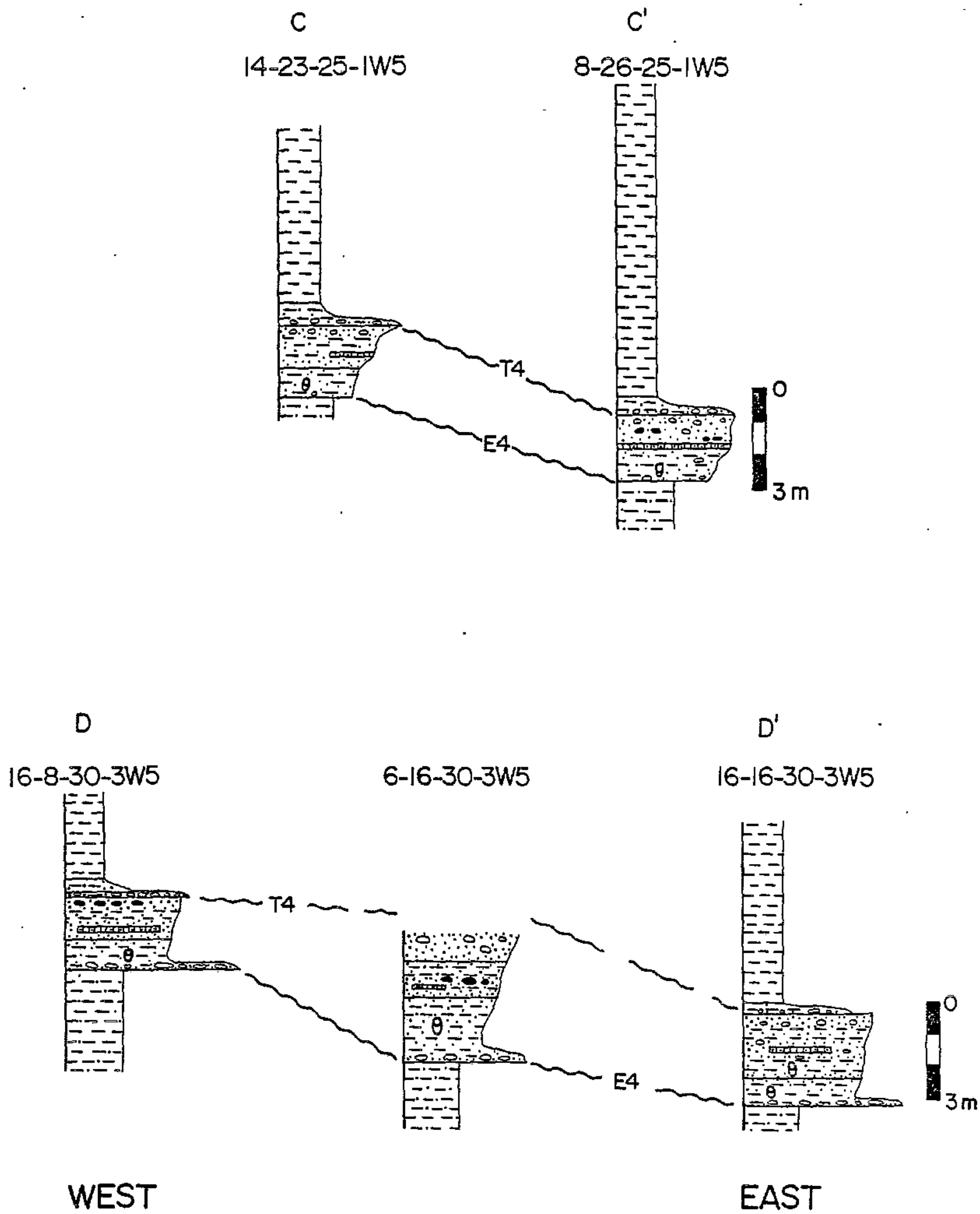
The lateral facies sequence and lower contact geometry in BB' is similar to that in AA'. Facies 7 and facies 8 are best developed in the western core (16-31-35-7W5), while the muddier facies, facies 6 and facies 6-7B-GS are best developed in the eastern core (10-32-35-7W5). This suggests that the Burnstick Member becomes sandier towards the west and muddier towards the east.

The lower contact (E4) is also observed to drop across Caroline in the position of BB'. This drop is approximately 1.7 meters. The geometry of the upper contact (T4) can not be determined in this core section because the upper contact is not cored in 10-32-35-7W5.

Crossfield

Core cross section CC' consists of two cores from the southern part of Crossfield (Figure 4.12). Both of these cores have relatively thin developments of the Burnstick Member and do not exhibit the complete BM facies sequence.

Figure 4.12. Core cross sections CC' and DD' from Crossfield, located in Figure 4.9. These core cross sections are hung on the LM and are constructed perpendicular to the strike of Crossfield.


C
14-23-25-1W5
C'
8-26-25-1W5
T4
E4
0
3 m
D
16-8-30-3W5
6-16-30-3W5
D'
16-16-30-3W5
T4
E4
0
3 m
WEST
EAST

CROSSFIELD

The western core, 14-23-25-1W5, does not have a facies 7 or a facies 8 while the eastern core, 8-26-25-1W5, does not have a facies 6-7B-GS or a facies 8. The only lateral facies change observed in this core section is the sandier nature of the upper Burnstick Member in 8-26-25-1W5 than in 14-23-25-1W5. It appears that facies 6-7B-GS in the west changes into facies 7 in the east.

Both the lower and upper contacts drop approximately 1.9 meters from the west to the east in cross section CC'. The lower contact (E4) is relatively sharp, with the occurrence of a few 6 mm pebbles near the base of facies 6. In contrast, the upper contact is gradational.

The second core cross section from Crossfield, DD', consists of three cores from the northern part of the field (Figure 4.12). This core cross section has two cores that penetrate the entire Burnstick Member (16-8-30-3W5 and 16-16-30-3W5) and one core that penetrates the lower 80% of the Burnstick Member (6-16-30-3W5).

In the two cores that penetrate the Burnstick Member, the complete BM facies sequence is not observed. Neither 16-8-30-3W5 nor 16-16-30-3W5 has a facies 7 or a facies 8. In contrast, 6-16-30-3W5 does have a minor development of facies 7 near the top of the core. It is difficult to determine the lateral facies relationships for core cross section DD' due to the incomplete penetration of the Burnstick Member in core 6-16-30-3W5. The only conclusion that can be made about the lateral facies relationships is that the sandstone facies, facies 7, is best developed in the central part of Crossfield.

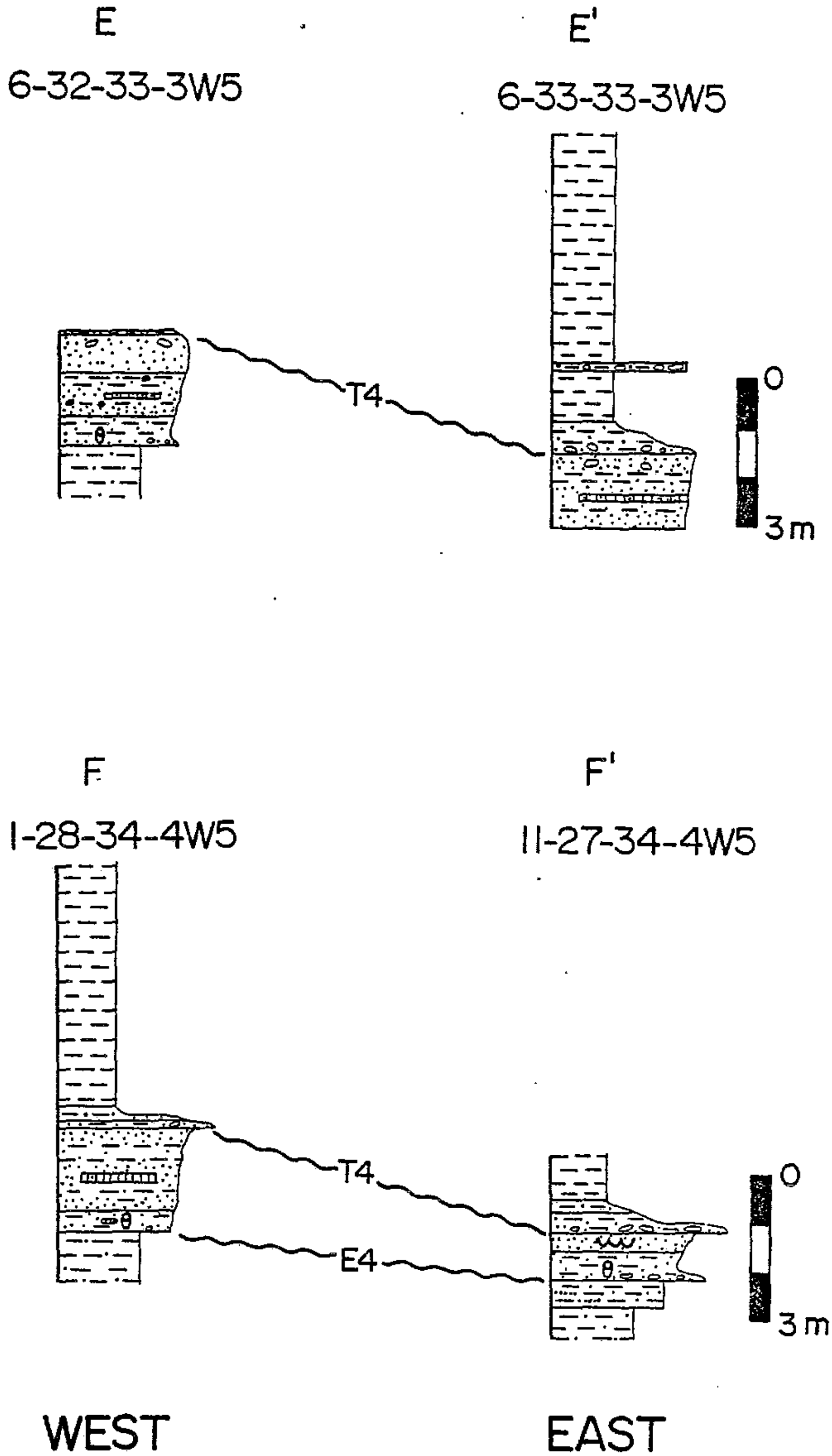
All of the lower contacts in core cross section DD' are extremely sharp. Pebbles greater than 15 mm in diameter are observed at the base of facies 6 in 16-8-30-3W5 and 16-16-30-3W5. The lower contact, E4, drops approximately 3.4 meters from the southwest to the northeast.

The upper contact, T4, is not observed in 6-16-30-3W5, but is correlated above the core using the resistivity well log. In contrast to the extremely sharp lower contact, the upper contact is gradational. The upper contacts in 16-8-30-3W5 and 16-16-30-3W5 are defined by the transition from a pebbly facies 6-7B-GS into a facies 6P. Both of these contacts are gradational and are difficult to pick in the core. The upper contact drops approximately 2.8 meters from the southwest to the northeast across DD'.

Garrington

Core cross section EE' is located in the central part of Garrington and it consists of two cores (Figure 4.13). Neither of the cores has a complete BM facies sequence nor a complete LRRM facies sequence, which makes it difficult to determine the lateral facies relationships. The core from 6-32-33-3W5 is truncated at the top of the Burnstick Member, while the core from 6-33-33-3W5 is truncated near the base of the Burnstick Member.

Figure 4.13. Core cross sections EE' and FF' from Garrington, located in Figure 4.9. Both of these core cross sections are hung on the LM and are constructed perpendicular to the strike of Garrington.


E
E'
6-32-33-3W5
6-33-33-3W5
T4
0
3m
F
F'
1-28-34-4W5
11-27-34-4W5
T4
E4
0
3m
WEST
EAST

GARRINGTON

The two conclusions that can be drawn from cross section EE' are, the Burnstick Member becomes sandier towards the west, and the upper contact, T4, drops from west to east across the field. The first conclusion is based on the transition from facies 7 in 6-32-33-3W5 to facies 6-7B-GS in 6-33-33-3W5 near the top of the BM facies sequence. This conclusion is based on a very limited amount of core data and it should be used with caution when applied elsewhere.

Cross section FF' also consists of two cores from the central area of Garrington and is located north of cross section EE' (Figure 4.13). The two cores in cross section FF' penetrate the entire Burnstick Member, revealing both the upper and lower contacts with the surrounding sediments.

The BM facies sequence thins from 1-28-34-4W5 into 11-27-34-4W5, while the LRRM facies sequence becomes thicker. Facies 6 and facies 6-7B-GS comprise the BM sequence in 1-28-34-4W5, while facies 6 and facies 7 comprise the BM sequence in 11-27-34-4W5. The occurrence of a thin facies 7 in 11-27-34-4W5 might be equivalent to a sandstone bed of facies 6-7B-GS in 1-28-34-4W5. If this is the case, there are no significant lateral facies changes from west to east across FF'.

Both the lower contact (E4) and the upper contact (T4) drop down towards the northeast across FF'. The E4 contact drops approximately 1.3 meters, while the T4 contact drops approximately 3.2 meters. This observation is consistent with the geometry of the E4 and the T4 contacts in the other core cross sections.

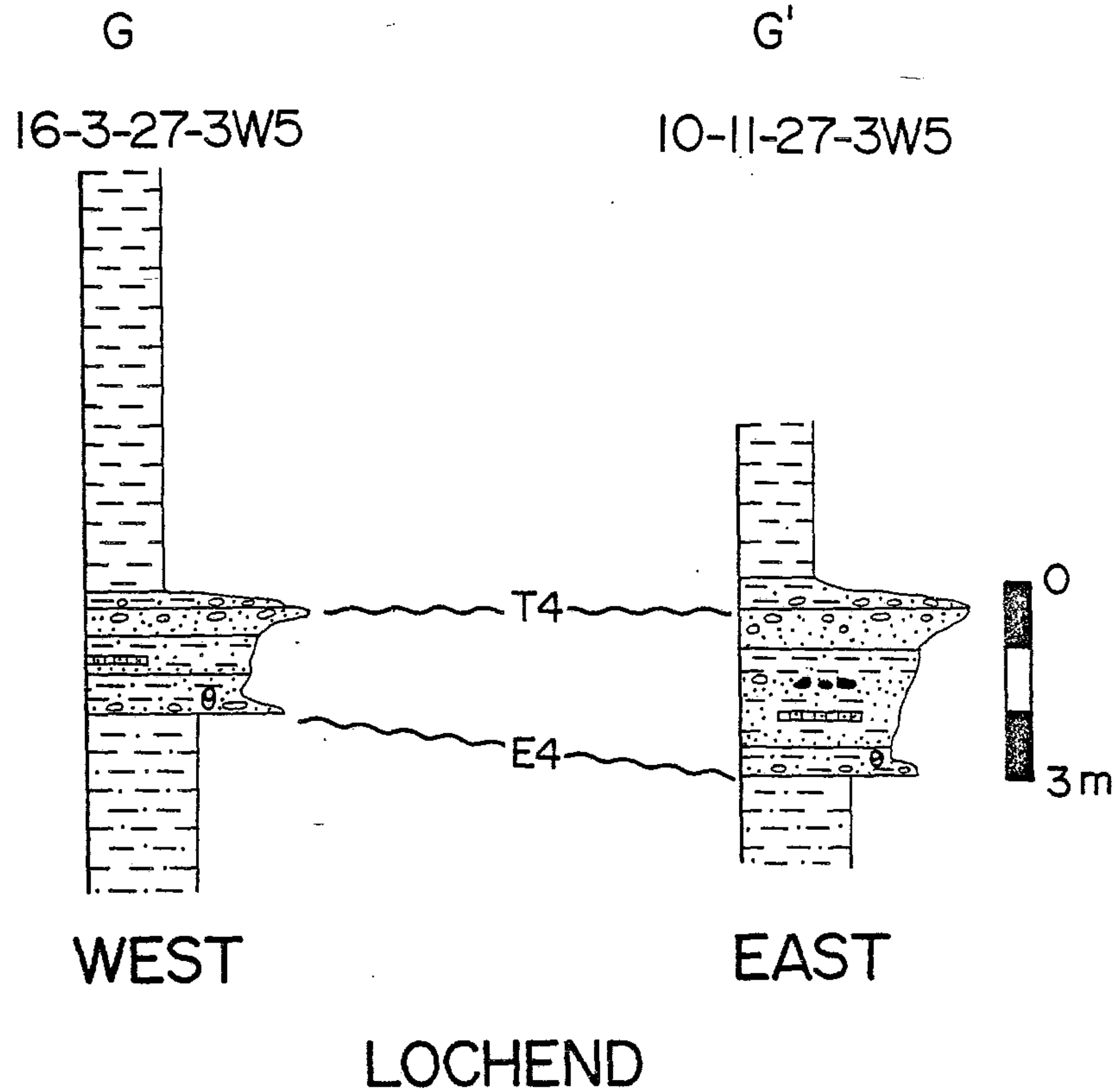
Lochend

Core cross section GG' is the only core cross section from Lochend and is located in the southern part of the field (Figure 4.14). This core cross section consists of two cores that penetrate the entire Burnstick Member in this area.

Complete BM facies sequences, with the exception of facies 8, are observed in both of the cores. This is considered to be a complete sequence as only one out of twelve Lochend cores have a facies 8. The Burnstick Member becomes thicker from the west to the east in cross section GG'. Most of this increase in thickness is attributed to the much thicker facies 6-7B-GS in 10-11-27-3W5 than in 16-3-27-3W5. No significant lateral facies change is observed.

The lower contact, E4, drops approximately 1 meter from the west to the east, while the upper contact remains horizontal. The geometry of the upper contact in GG' is unusual when compared to the geometry of the other upper contacts. In most core cross sections, the upper contact mirrors the lower contact by dropping down from the west to the east. However, in the GG' core cross section the upper contact is horizontal.

Figure 4.14. Core cross section GG' from southern Lochend, located in Figure 4.9. This core cross section is hung on the lower marker (LM) and is constructed perpendicular to the strike of Lochend.


G
16-3-27-3W5
G'
10-11-27-3W5
T4
E4
0
3m
WEST
EAST
LOCHEND

Summary

Many similarities are observed when comparing the core cross sections from the four fields. This summary will relate the main observations from the seven core cross sections regarding the lateral facies changes and the geometry of the two contacts.

There is no single, consistent lateral facies relationship observed in the seven core cross sections. The BM sequences can become: (1) thicker and sandier towards the west (eg. AA', Figure 4.11), (2) thinner and muddier towards the west (eg. GG', Figure 4.14), or (3) show no trend at all (eg. DD', Figure 4.12). This suggests that there is no consistent lateral facies relationship perpendicular to the strike of the fields.

In contrast, there is a consistent relationship between the geometries of the two contacts in the seven core cross sections. In each core cross section, the contacts either dip towards the east/northeast or they are horizontal. Eleven out of the twelve contacts dip towards the east/northeast, while the other contact is horizontal. A maximum drop of 3.4 meters is observed in cross section DD' from Crossfield (Figure 4.12).

4.4 Combined Core and Well Log Cross Sections

Two different sets of combined core and well log cross sections have been developed. The first set of combined core and well log cross sections is used to relate the stratigraphic position and the facies sequence of the off-field sediments to the east and west, to those on-field. This is accomplished by constructing two combined cross sections, one from Garrington and one from Crossfield (Figure 4.15).

The other set of combined core and well log cross sections is used to determine the lateral facies relationships and the geometry of the Burnstick Member contacts parallel to the strike of the fields. Two combined sections, one from Garrington and one from Crossfield are used for this purpose. It is believed that the lateral facies relationships in these two fields will be representative of the Burnstick Member in the study area. For this reason, combined core and well log cross sections parallel to the field strikes of Caroline and Lochend were not constructed.

Off-field/On-field Facies Relationships

Cross section HH' consists of three cores and three well logs from central Garrington (Figures 4.15 and 4.16). This cross section is constructed to show the relationship between sediments on-field and off-field to the west.

Figure 4.15. The location map for the two combined core and well log cross sections that relate the on-field Burnstick Member sediments to the off-field west (HH') and the off-field east (JJ') Burnstick Member sediments.

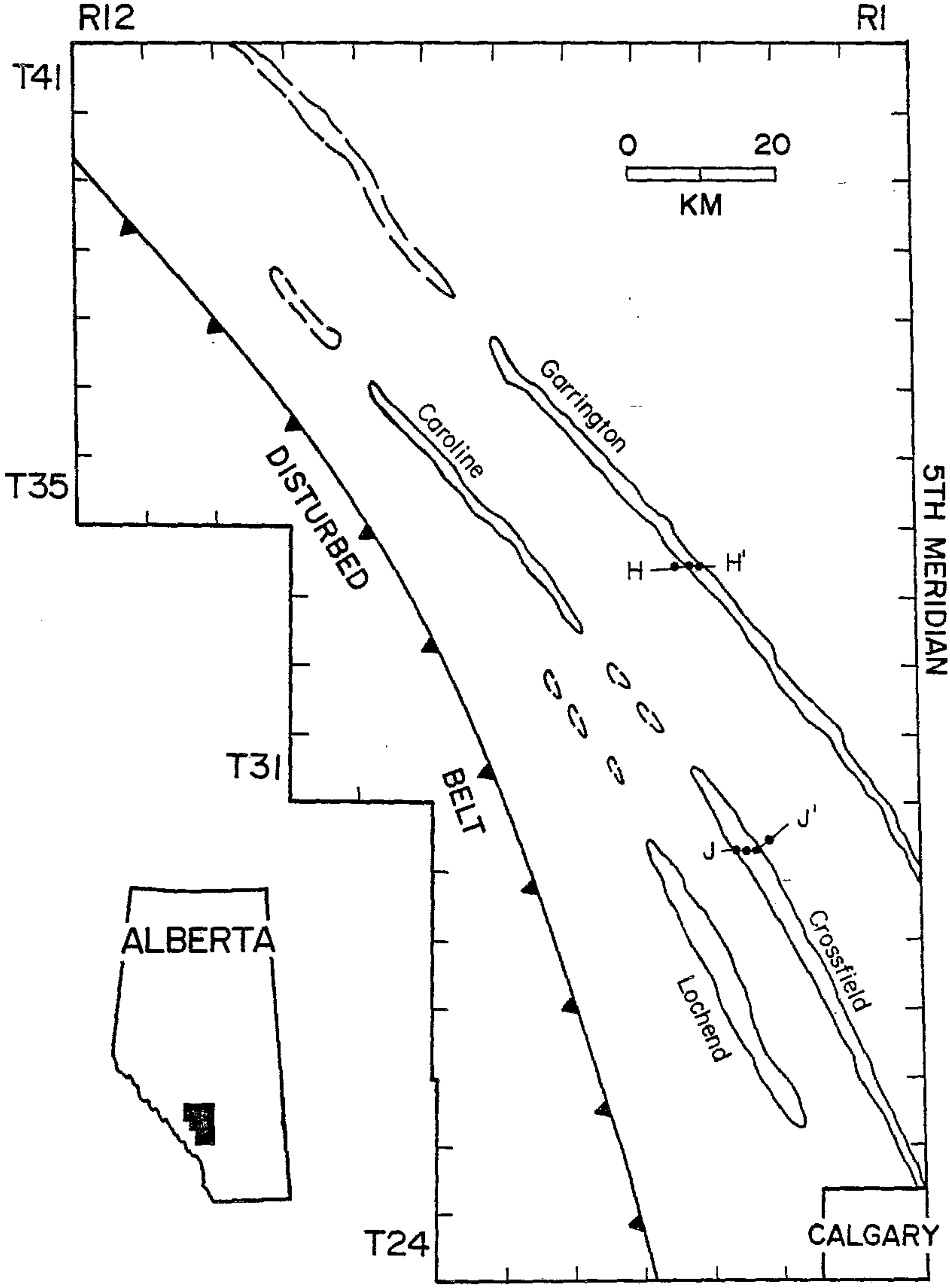
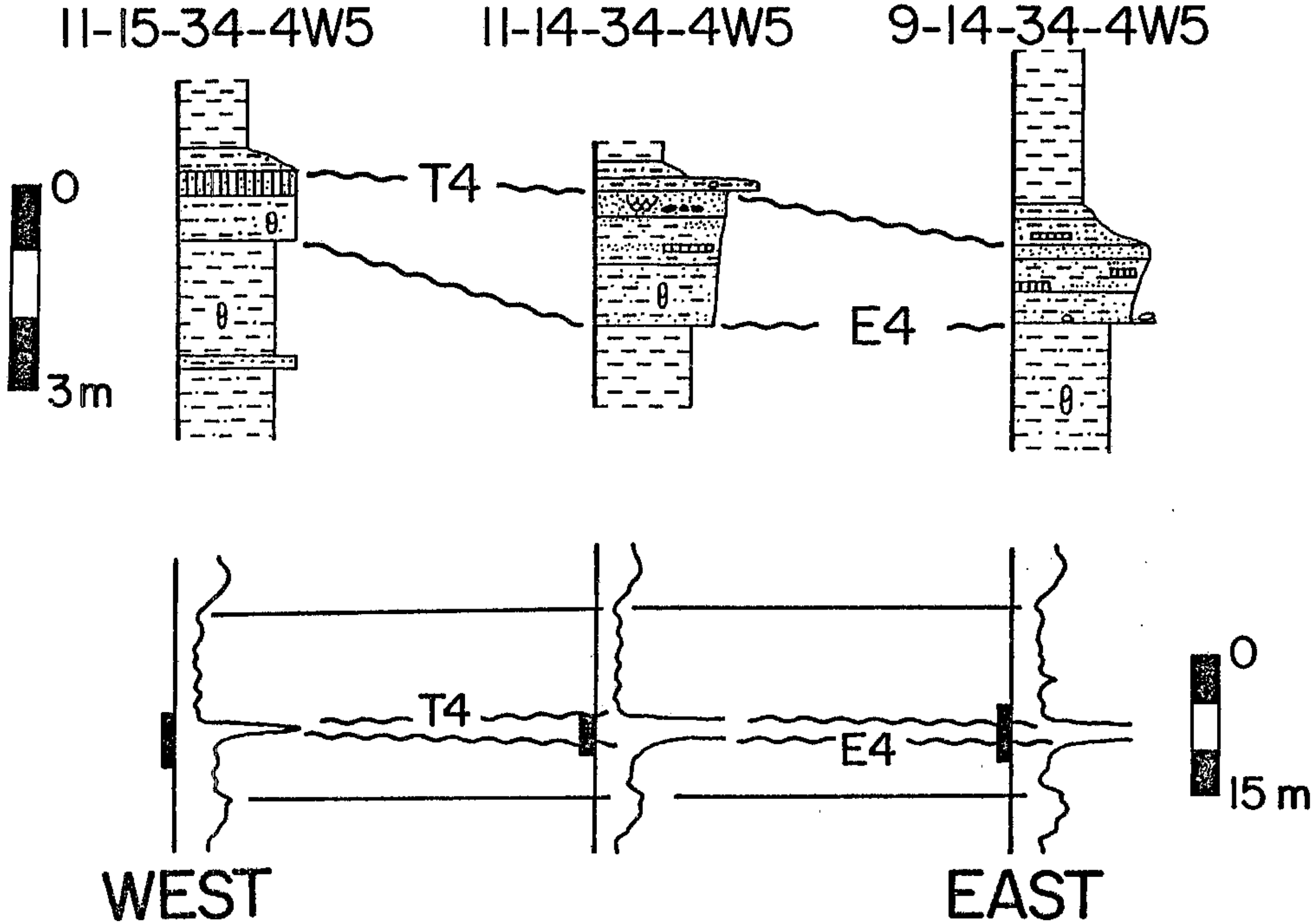

R12
R1
T41
T35
T31
T24
0
20
KM
Garrington
Caroline
DISTURBED
BELT
H
H'
5TH MERIDIAN
J
J'
Crossfield
Lochend
ALBERTA
CALGARY

Figure 4.16. Combined core and well log cross section HH' through central Garrington, located in Figure 4.15. Note the lateral facies change from 11-15-34-4W5 to 11-14-34-4W5. The stratigraphic position of the Burnstick Member and the prominence of the corresponding well log response in 11-15-34-4W5 are typical of most off-field west Burnstick Member sediments.

GARRINGTON



The off-field sediments are observed in 11-15-34-4W5, and consist of a facies 6, a gritty siderite and an upper facies 1P. In comparison to the on-field sediments, the off-field sediments are thinner, finer grained and rest at a higher stratigraphic interval. This relationship is typical for the four fields.

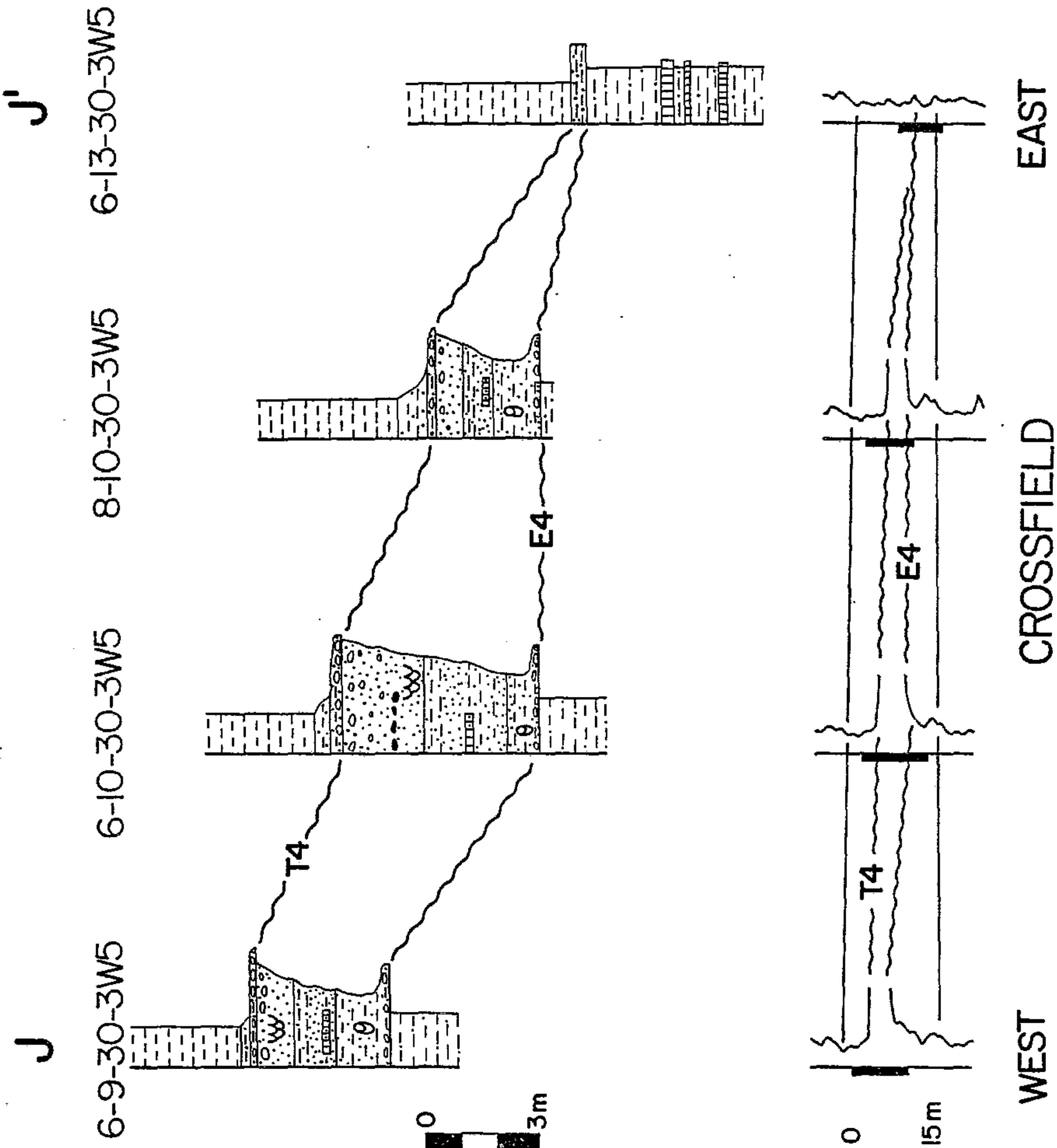
It is also important to note the prominence of the off-field well log response in 11-15-34-4W5 (Figure 4.16). To the west, the well log responses are very well defined and are easy to identify on the resistivity well logs.

Cross section JJ' consists of four cores and the corresponding well logs from the northern part of Crossfield (Figure 4.17). The purpose of this combined core and well log cross section is to show the relationship between on-field sediments and those off-field to the east.

The off-field sediments are observed in 6-13-30-3W5 and consist of approximately 0.3 meters of facies 1B. In comparison to the on-field sediments, those off-field are thinner, finer grained and rest at a lower stratigraphic interval. These characteristics are consistently observed in other sediments off-field to the east.

The corresponding off-field well log signature is difficult to recognize in 6-13-30-3W5. This signature is not very prominent when compared to the signature off-field to the west (Figure 4.16).

Figure 4.17. Combined core and well log cross section JJ' from northern Crossfield, located in Figure 4.15. Note the facies change from 8-10-30-3W5 to 6-13-30-3W5. The stratigraphic position and the character of the well log response for the core off-field to the east (6-13-30-3W5) is typical of other off-field to the east responses. The off-field to the east sediments are at a lower stratigraphic interval and have a less prominent well log response than the off-field to the west sediments. This can be observed by comparing Figure 4.16 and Figure 4.17.


J
J'
6-9-30-3W5
6-10-30-3W5
8-10-30-3W5
6-13-30-3W5
T4
E4
0
3m
WEST
CROSSFIELD
EAST
T4
E4
0
15m

Lateral Facies Relationships Parallel to the Fields

Combined core and well log cross sections were constructed parallel to the strike of Garrington and Crossfield (Figure 4.18). The purpose of these two cross sections is to determine if there are any significant lateral facies changes or changes in the geometry of the E4 and the T4 contacts parallel to the strike of the fields.

Cross section XX' consists of nine cores and their corresponding resistivity well logs from Garrington (Figure 4.19). This cross section is hung on the lower marker and is approximately 80 kilometers long.

The most striking lateral facies change in XX' is the transition from facies 8 in 4-3-37-6W5 to a thin facies 7 in 11-27-35-5W5. Over one meter of conglomerate (facies 8) is observed in 4-3-37-6W5, while 11-27-35-5W5 has no facies 7 nor a facies 8.

The only other lateral facies change in cross section XX' is the thinning and the fining of the Burnstick Member towards the southeast. As the Burnstick Member thins towards the southeast, the contact between the Hornbeck Member and Burnstick Member rises approximately three meters. In contrast to the lower contact, the upper contact between the Burnstick Member and the Raven River Member remains horizontal.

Cross section YY' consists of nine cores and their corresponding well logs from Crossfield (Figure 4.20). The

Figure 4.18. The location map for the combined core and well log cross sections parallel to the strike of Garrington and Crossfield. Cross section XX' is located in Garrington and cross section YY' is located in Crossfield.

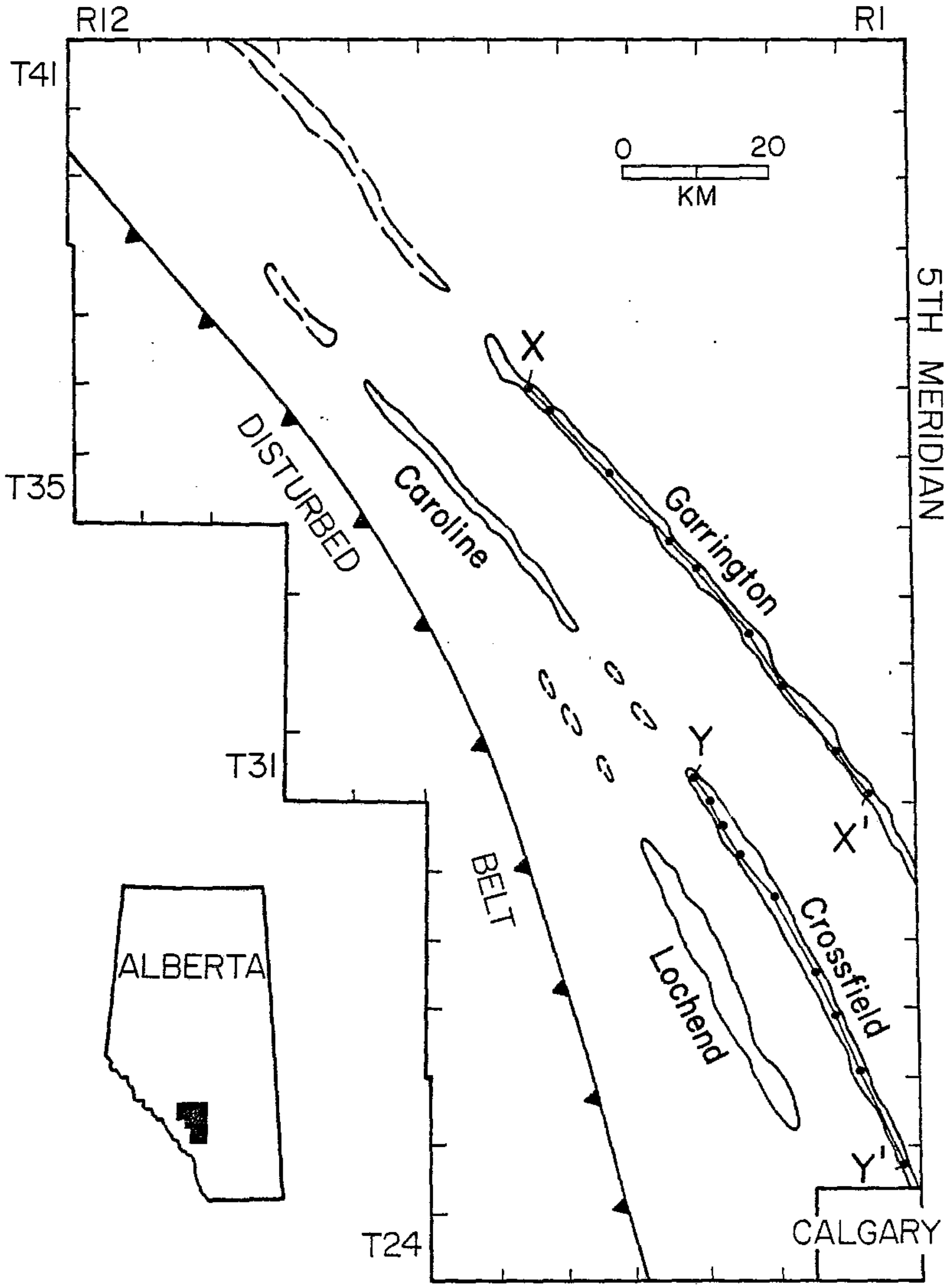

R12
R1
T41
T35
T31
T24
0
20
KM
5TH MERIDIAN
X
X'
Y
Y'
DISTURBED
BELT
Caroline
Garrington
Crossfield
Lochend
ALBERTA
CALGARY

Figure 4.19. Cross section XX' from Garrington showing the lateral facies changes parallel to the strike of the field. Note the thinning and fining of the Burnstick Member towards the southeast, and also the rising of the Burnstick Member base. Refer to Figure 4.10 for a facies key.

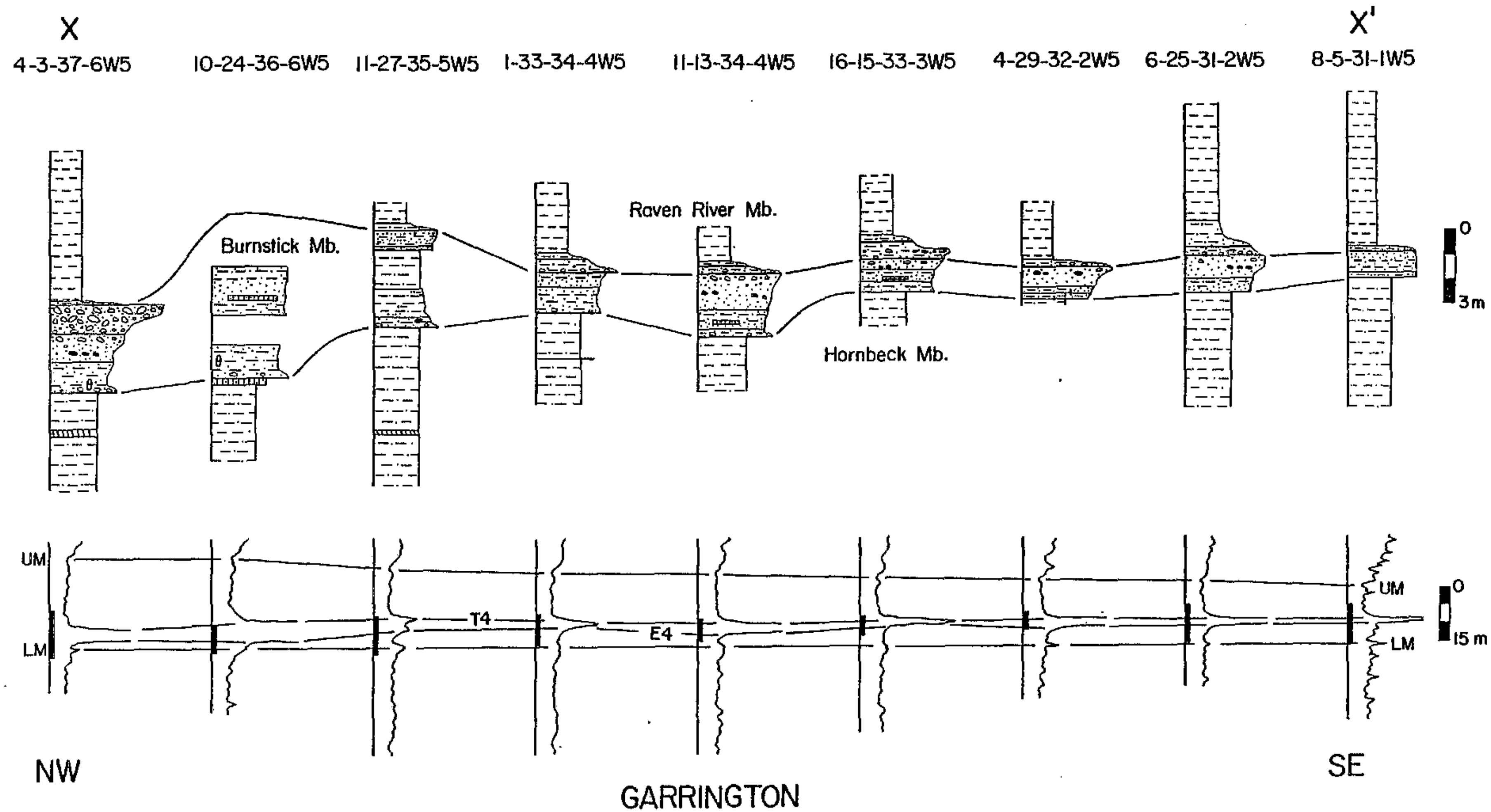
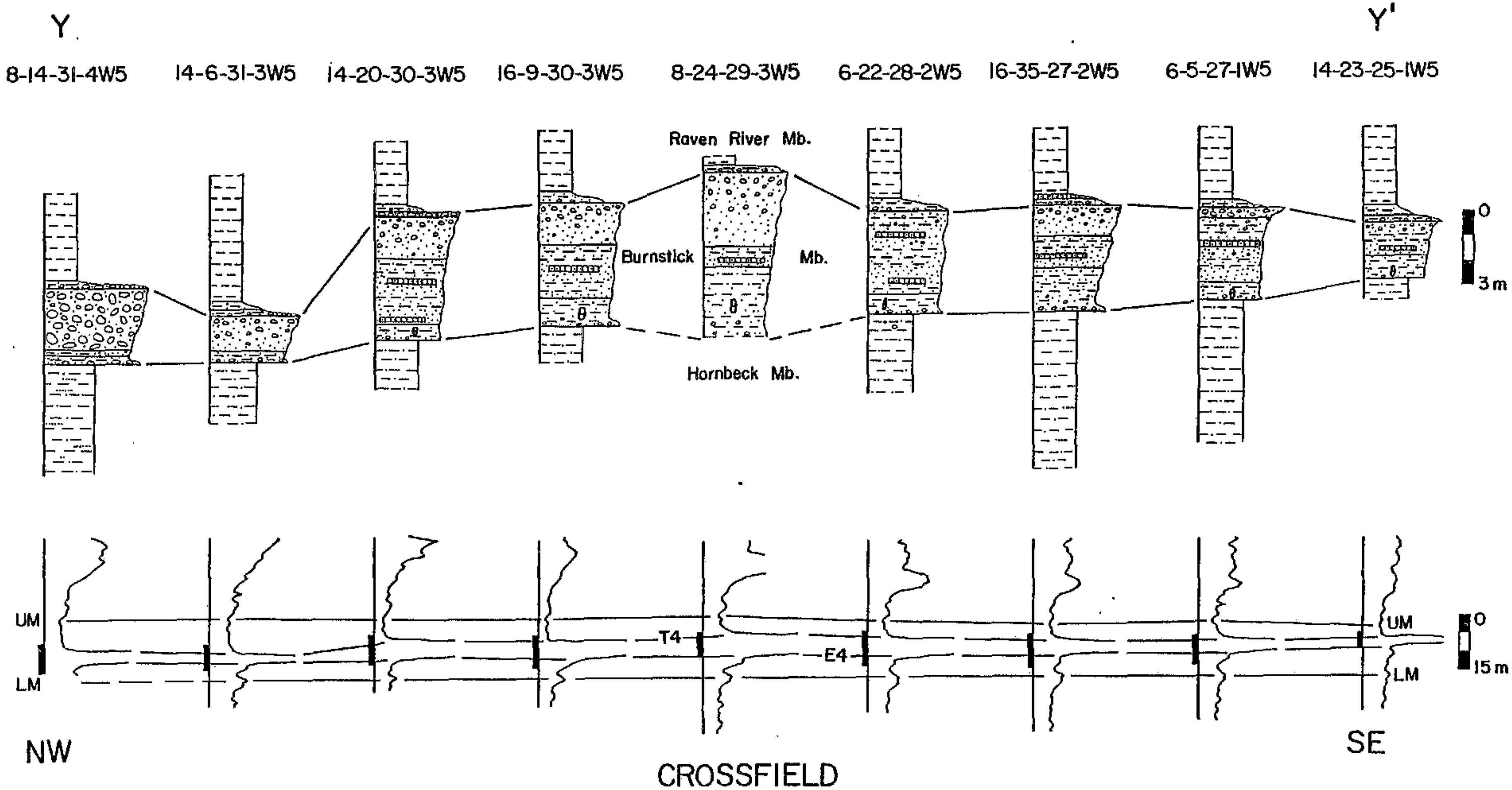

X
X'
4-3-37-6W5
10-24-36-6W5
11-27-35-5W5
1-33-34-4W5
11-13-34-4W5
16-15-33-3W5
4-29-32-2W5
6-25-31-2W5
8-5-31-1W5
Burnstick Mb.
Raven River Mb.
Hornbeck Mb.
0
3 m
UM
LM
T4
E4
UM
LM
0
15 m
NW
SE
GARRINGTON

Figure 4.20. Cross section YY' from Crossfield. This cross section is oriented parallel to the strike of Crossfield. Note the decrease in grain size from the northern part of the cross section into the southern part of the cross section.



Y
Y'
8-14-31-4W5
14-6-31-3W5
14-20-30-3W5
16-9-30-3W5
8-24-29-3W5
6-22-28-2W5
16-35-27-2W5
6-5-27-1W5
14-23-25-1W5
Raven River Mb.
Burnstick
Mb.
Hornbeck Mb.
0
3 m
UM
LM
T4
E4
UM
LM
0
15 m
NW
SE
CROSSFIELD

Burnstick Member is thicker in these cores than in the cores from cross section XX'.

The lateral facies changes and changes in the geometry of the lower contact (E4) observed in cross section YY' are similar to those observed in cross section XX'. The most northerly well in YY' contains 2.43 meters of facies 8 (conglomerate) and is the only core in cross section YY' that contains over 0.3 meters of conglomerate. A sharp lateral facies change is observed from 8-14-31-4W5 into 14-6-31-3W5, because the latter core does not have a facies 8. This lateral facies change is identical to the lateral facies change observed in the northern part of cross section XX'.

The general trend of the Burnstick Member facies in cross section YY' is to become thinner and finer towards the southeast. A comparison between the facies in 16-9-30-3W5 and those in 14-23-25-1W5 highlights this point. The base of the Burnstick Member also rises from the northwest to the southeast in cross section YY', which is similar to the trend of the Burnstick Member in cross section XX'.

4.5 Similarities Between the Fields

The 25 different well log, core, and combined core and well log cross sections are used to identify the lateral facies relationships and the two dimensional geometry of the Burnstick Member sediments. Most of the observations and conclusions derived from a study of the Burnstick Member sediments in any one field can be equally applied to the Burnstick Member of the other fields in the study area. With this in mind, it is important to identify similar characteristics of the Burnstick Member in the four fields.

The following characteristics are consistently observed in the different cross sections perpendicular to the field strike:

(1) the base of the Burnstick Member drops from west to east across the fields,

(2) the top of the Burnstick Member drops from west to east across the fields,

(3) the Burnstick Member off-field to the west is thicker, coarser and rests at a higher stratigraphic interval than that to the east,

(4) the two dimensional sandbody geometry of the Burnstick Member defines a sigmoidal or an S-shaped profile from west to east, and,

(5) there are no consistent on-field lateral facies changes.

These five points describe the most significant characteristics of the Burnstick Member common to the fields perpendicular to their strike.

Based on the two combined core and well log cross sections parallel to the strike of Crossfield and Garrington, it is possible to make the following conclusions about the Burnstick Member parallel to the field strike:

(6) the Burnstick Member becomes thinner and finer grained towards the southeast, and,

(7) the base of the Burnstick Member rises towards the southeast.

These seven conclusions suggest that the Burnstick Member has a consistent lateral facies sequence and a consistent two dimensional sandbody geometry perpendicular and parallel to the strike of the four fields. The thickness of the Burnstick Member facies and the stratigraphic position of the Burnstick Member do vary between the fields, as can be observed when comparing the Burnstick Member sediments of Garrington to those at Crossfield. However, the basic facies sequence, the off-field/on-field facies relationships and the two dimensional geometry of the Burnstick Member remain consistent in the four fields.

It is possible that the consistent drop in the lower and upper contacts across the fields defines two erosional surfaces. One of these erosional surfaces would be located at the Burnstick -- Raven River Member contact, while the other erosional surface would be located at the Hornbeck--Burnstick Member contact. Further study of the three dimensional geometry of these contacts is necessary to confirm this hypothesis.

CHAPTER 5: Sandbody and Erosional Surface Geometry

5.1 Introduction

In order to develop a better understanding of the sandbody geometry and the geometry of the E4 surface it is necessary to study these intervals in three dimensions. In the previous chapter, the two dimensional geometry of the Burnstick Member and the geometry of the contacts were studied in detail. This was accomplished by constructing core and well log cross sections across the fields. The results from these cross sections illustrate the two dimensional geometry of the Burnstick Member at specific locations in the fields.

The purpose of this chapter will be to examine the three dimensional geometry of the Burnstick Member in each of the four fields. This will be accomplished by constructing two isopach maps for each field, one showing the thickness of the Burnstick Member and the other showing the topography on the E4 surface. It will be possible to test the hypothesis that the E4 surface is erosive by studying the three dimensional geometry of this surface in the four fields.

This chapter is divided into six sections. The next four sections will describe the isopach maps and cross section for each field, and will explore the relationship between the two isopached intervals. The final section will summarize the observations of Sections 5.2 to 5.5 and will present a list of similarities for the four fields.

5.2 Caroline Isopach Maps

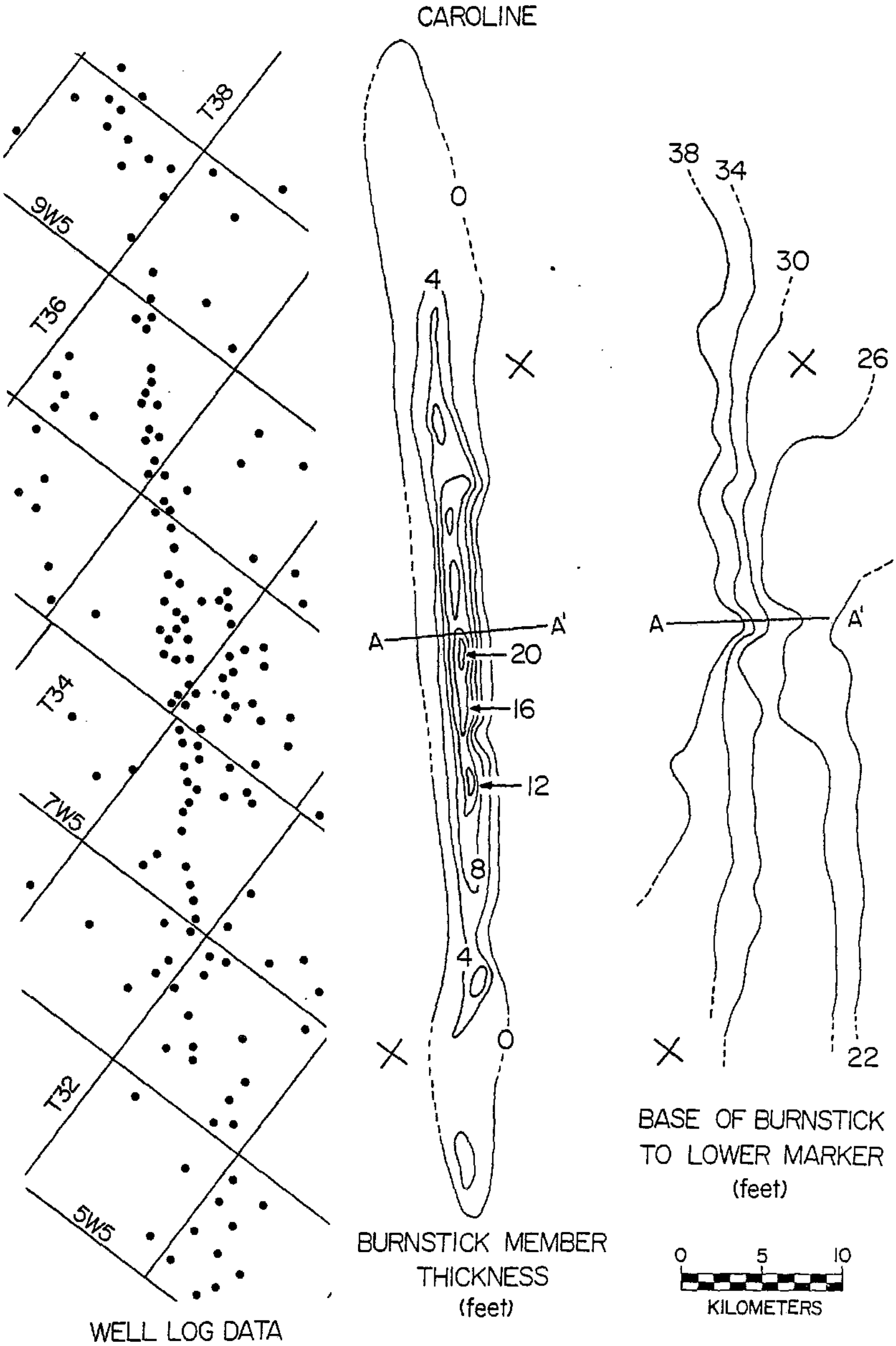
Data from over 150 well logs in the Caroline area were used to construct the two isopach maps for this field (Figure 5.1). In each well log, four markers were consistently picked: the upper marker (UM), the top of the Burnstick Member (TB), the base of the Burnstick Member (BB), and the lower marker (LM). The first isopach map shows the thickness of the Burnstick Member (TB-BB) coarse sediment package in Caroline, while the second isopach map shows the thickness between the base of the Burnstick Member (BB) and the lower marker (LM) underneath Caroline.

The Burnstick Member sediments in the Caroline field can be traced from Township 32/Range 4W5 in the southeast up to Township 38/Range 9W5 in the northwest (Figure 5.1). The Caroline field has a strike of 318°, is approximately 72 kilometers long and is 2.5 to 5.4 km wide. This outlines an extremely long and narrow sandbody.

The Burnstick Member is thickest in central Caroline (>20 feet) and thins symmetrically on all sides of the field. In Townships 32, 33 and 37 the Burnstick Member is extremely thin (<4 feet) and is identified as a subdued resistivity well log response.

Figure 5.1. The Burnstick Member thickness (TB-BB) and the base of the Burnstick Member to lower marker (BB-LM) isopach maps for Caroline. The second isopach map, BB-LM, shows the topography on the E4 surface. The location of the well log data used for the two isopach maps is shown to the left.

The dashed isopach lines indicate the areas of poor well log control. Note the location of cross section AA' in central Caroline.

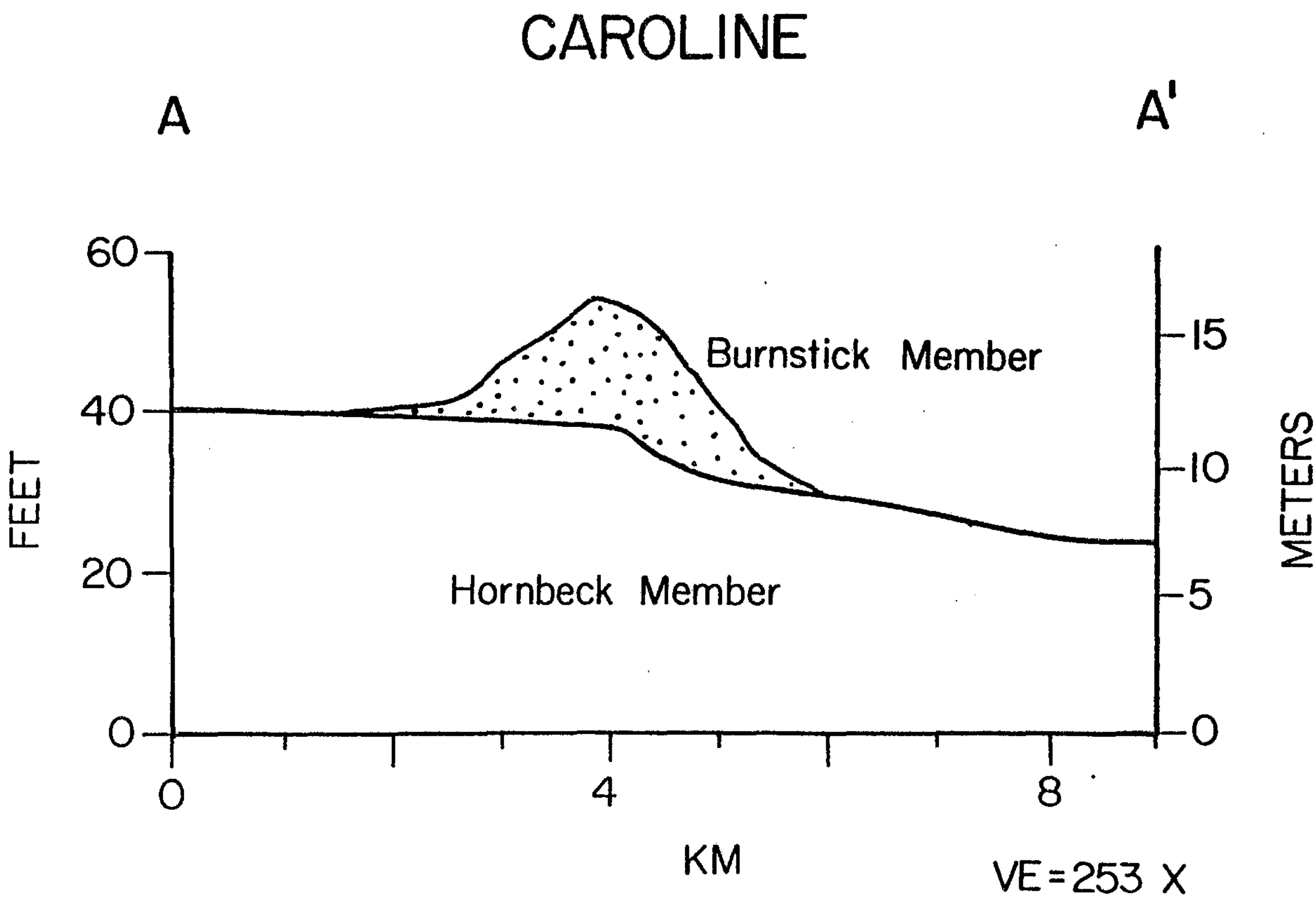

CAROLINE
T38
9W5
T36
T34
7W5
T32
5W5
WELL LOG DATA
0
4
A
A'
20
16
12
8
4
0
BURNSTICK MEMBER
THICKNESS
(feet)
38
34
30
26
22
BASE OF BURNSTICK
TO LOWER MARKER
(feet)
0 5 10
KILOMETERS

The second isopach map for Caroline, the BB-LM map, shows the topography on the E4 surface prior to the deposition of the Burnstick Member (Figure 5.1). The BB-LM interval decreases from 38 feet in the southwest to 26 feet in the northeast underneath Caroline. A 12 foot drop in the BB-LM interval is observed over a distance of 4 to 10 km.

The E4 surface dips 0.03° to 0.05° NE underneath Caroline relative to the horizontal lower marker. The dipping E4 surface suggests one of three things: (1) the BB-LM interval thins from the west to the east, (2) there is a topography on the LM surface that "steps up" towards the east, or (3) there is a topography on the E4 surface that "cuts down" towards the east. The latter two possibilities suggest that the thinning of the BB-LM interval is due to erosion on the LM or E4 surface. The "cutting down" of the E4 surface from west to east underneath Caroline is favoured because the LM is parallel to other lower markers. This suggests that the topography on the E4 surface is independent of the topography of the lower markers.

By superimposing two identical cross section lines from each isopach map it is possible to observe the relationship between the Burnstick Member sediments and the E4 surface in Caroline (Figure 5.2). Cross section AA' shows that the Burnstick Member sediments rest stratigraphically on top of the dipping E4 surface. This relationship is observed down the entire length of Caroline.

Figure 5.2. Cross section AA' from central Caroline. This cross section combines the data from the two isopach maps shown in Figure 5.1. Note the localization of the Burnstick Member on the dipping E4 surface.



CAROLINE
A
A'
Burnstick Member
Hornbeck Member
60
40
20
0
FEET
15
10
5
0
METERS
0
4
8
KM
VE = 253 X

5.3 Crossfield Isopach Maps

Measurements from over 190 well logs were used to construct two isopach maps for Crossfield (Figure 5.3). The first isopach map shows the thickness of the Burnstick Member (TB-BB), while the second isopach map shows the BB-LM interval.

The first isopach map shows that the Burnstick Member thins from 20 to 24 feet in the northern half of Crossfield to less than 16 feet in the southern half. The Burnstick Member sediments in Crossfield outline a sandbody that is 72 kilometers long and 3 - 4 kilometers wide.

The second isopach map (BB-LM) is constructed to show the topography on the E4 surface. It is difficult to identify the base of the Burnstick Member (BB) in many of the off-field resistivity well logs, and hence the topography on the E4 surface in the off-field areas is not well known.

The BB-LM stratigraphic interval thins perpendicular to the strike of Crossfield, from 34 feet in the southwest to less than 18 feet in the northeast. A 16 foot drop in the BB-LM interval occurs over a distance of 3 kilometers in the central part of Crossfield. The maximum slope observed on the E4 surface is 0.11°.

By comparing the two isopach maps, it is noted that the dipping E4 surface is oriented parallel to the strike of the Burnstick Member sediments in Crossfield. This suggests

Figure 5.3. The Burnstick Member thickness (TB-BB) and the base of the Burnstick Member to the lower marker (BB-LM) isopach maps for Crossfield. The data base used to construct these two isopach maps is shown towards the left.

The dashed isopach lines indicate areas of poor well log control. Note the location of cross section BB' in central Crossfield.

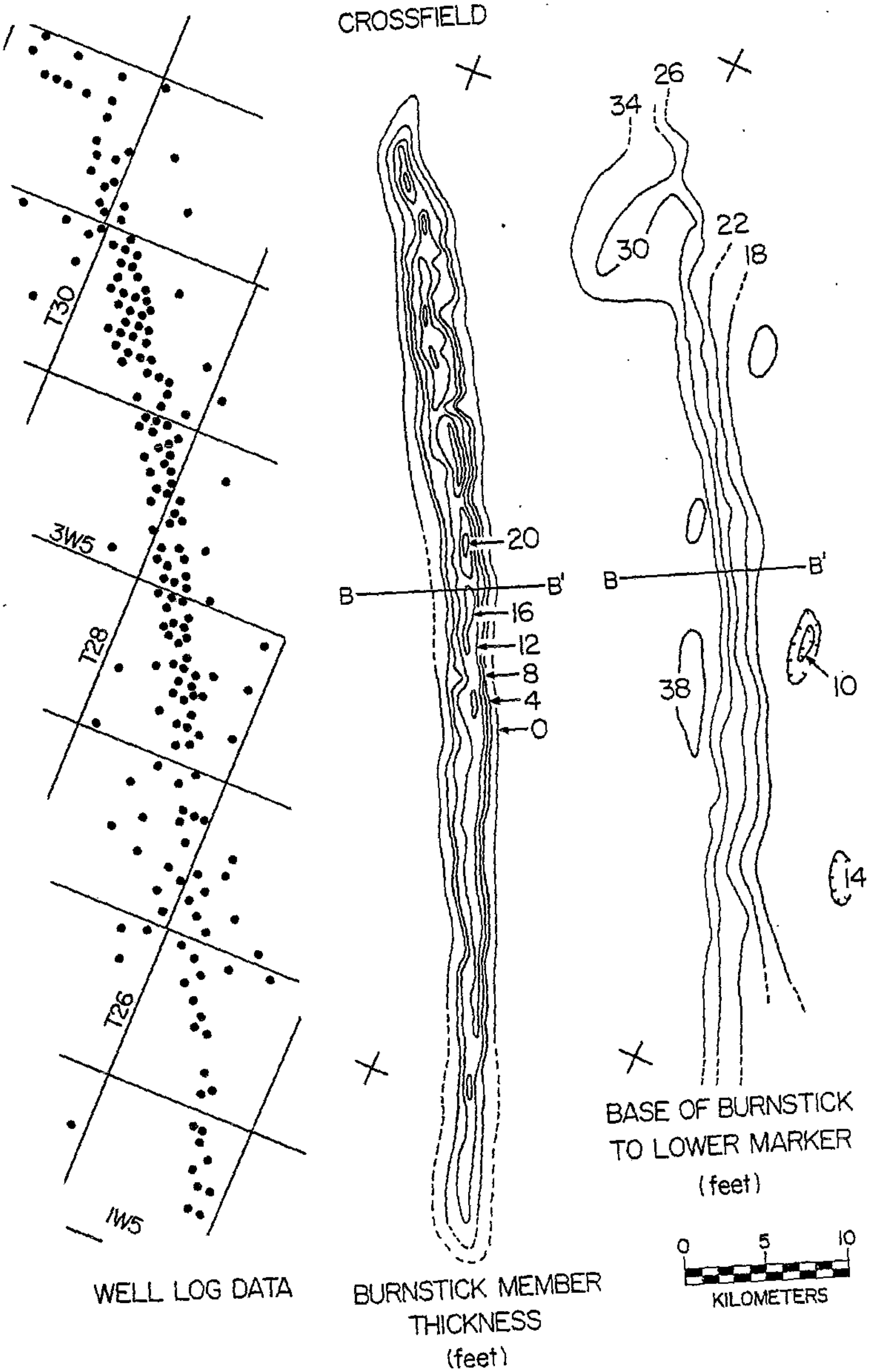
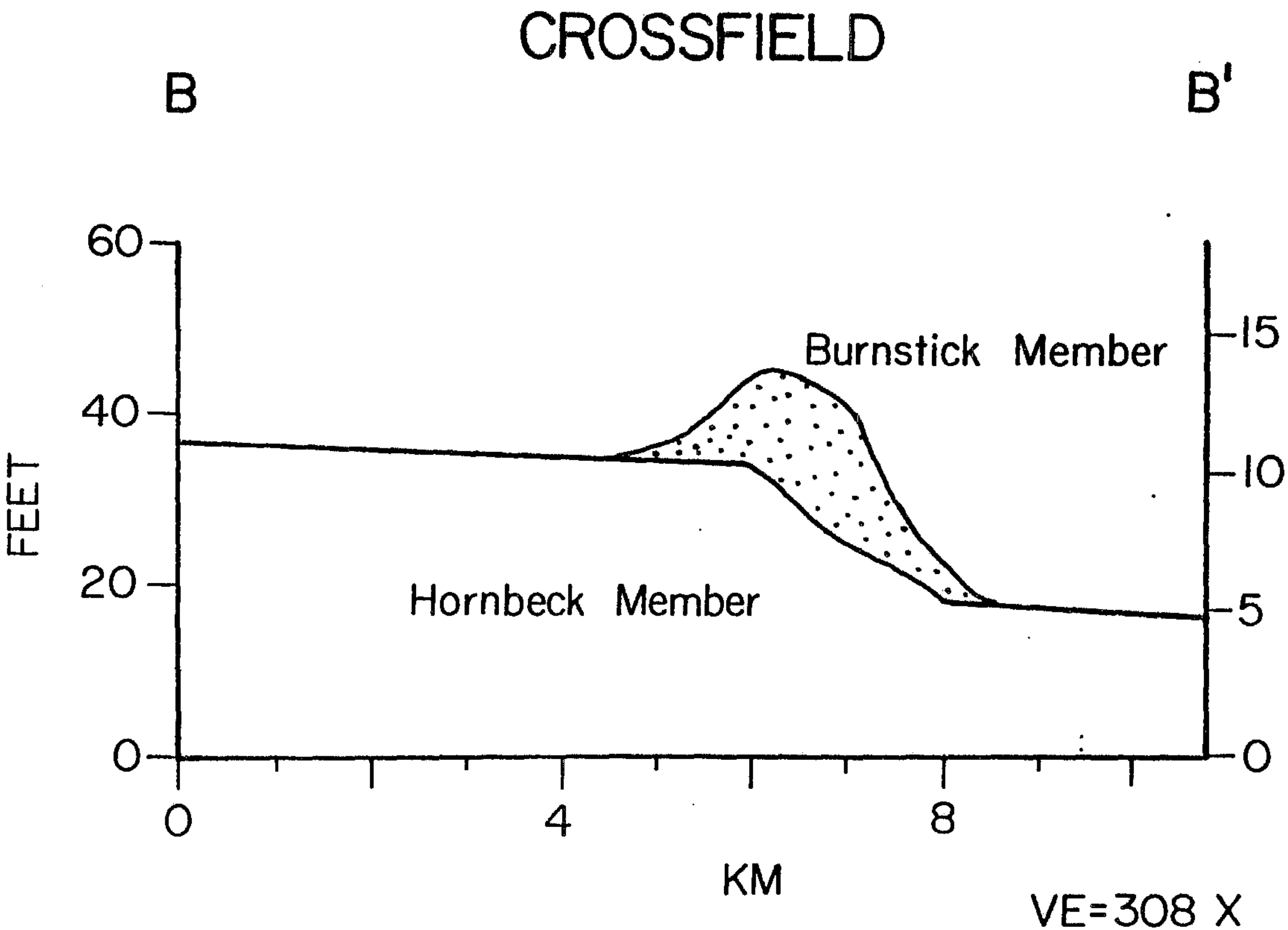

CROSSFIELD
T30
3W5
T28
T26
IW5
WELL LOG DATA
20
16
12
8
4
0
B
B'
BURNSTICK MEMBER
THICKNESS
(feet)
26
34
30
22
18
38
10
14
BASE OF BURNSTICK
TO LOWER MARKER
(feet)
0
5
10
KILOMETERS

Figure 5.4. Cross section BB' from central Crossfield. This cross section is constructed by superimposing the data from the two Crossfield isopach maps shown in Figure 5.3.

Note that the Burnstick Member sediments are concentrated on the dipping part of the E4 surface.


CROSSFIELD
B
B'
Burnstick Member
Hornbeck Member
FEET
METERS
60
40
20
0
15
10
5
0
0
4
8
KM
VE=308 X

that the topography on the E4 surface is related to the orientation of the Burnstick Member sediments in Crossfield. Further comparison of the two isopach maps is made in cross section BB' (Figure 5.4), which shows that the Burnstick Member sediments are localized in the one-sided scour of the E4 surface. This also suggests that the topography of the E4 surface is directly related to the Burnstick Member sediments in Crossfield.

5.4 Garrington Isopach Maps

Two isopach maps were constructed for Garrington that are based on data from over 230 resistivity well logs (Figure 5.5). The first isopach map shows the thickness of the Burnstick Member in Garrington, while the second isopach map shows the BB-LM interval underneath Garrington. Based on the data in the two isopach maps it appears that the Burnstick Member thins towards the SE, parallel to the field strike, and that the BB-LM interval thins towards the NE, perpendicular to the field strike. As indicated by the BB-LM isopach map, the E4 surface dips 0.04° to 0.08° underneath Garrington.

The three dimensional geometry of the E4 surface is relatively flat and is at a higher stratigraphic interval to the west than to the east. In cross section, this geometry outlines a step-like feature from west to east underneath Garrington.

Figure 5.5. The Burnstick Member thickness and the base of the Burnstick Member to the lower marker isopach maps for Garrington. The data base used to develop the two isopach maps is shown to the left.

The dashed isopach lines indicate the areas of poor well log control. Note the location of cross section CC' in southern Garrington.

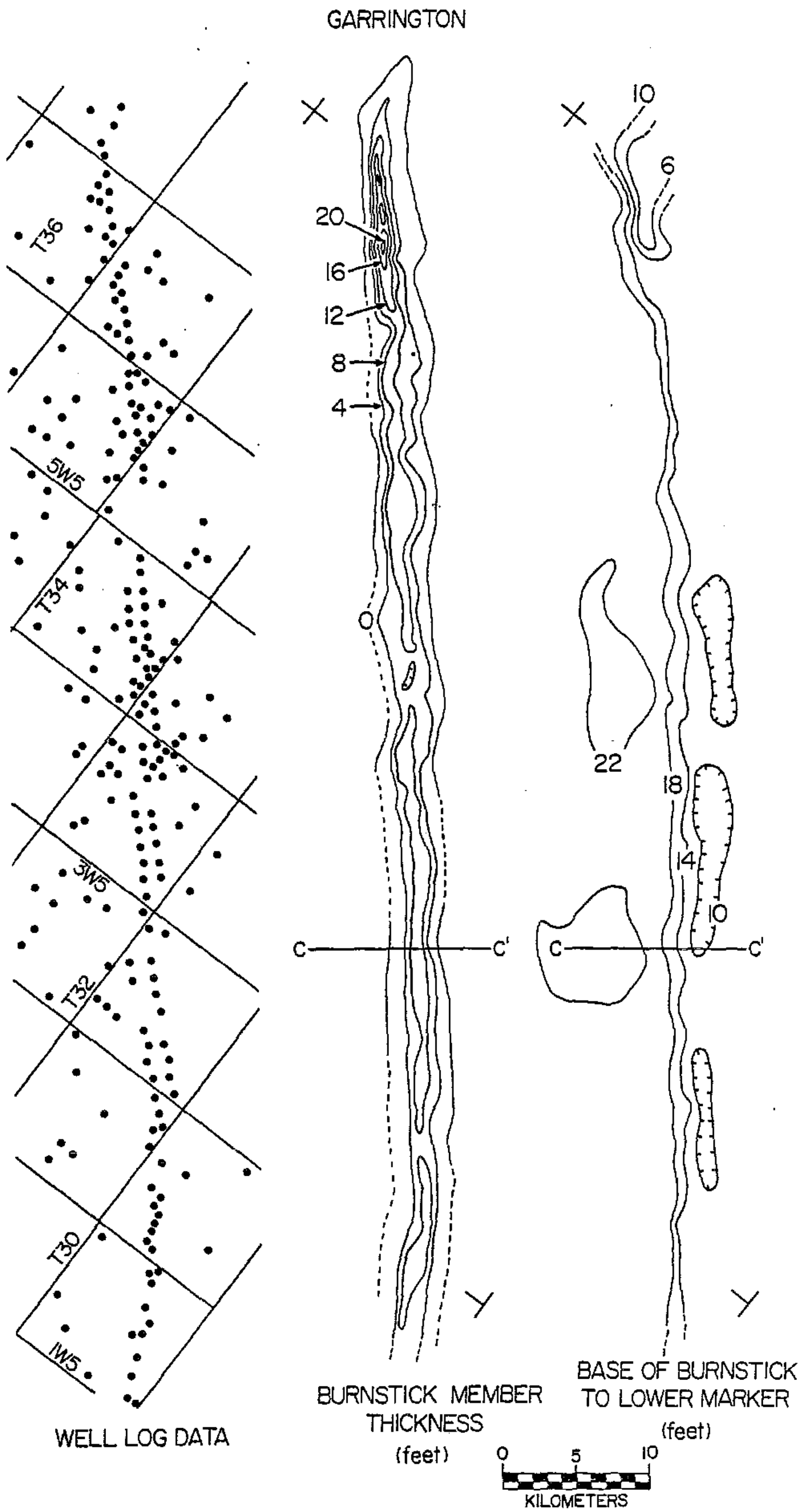
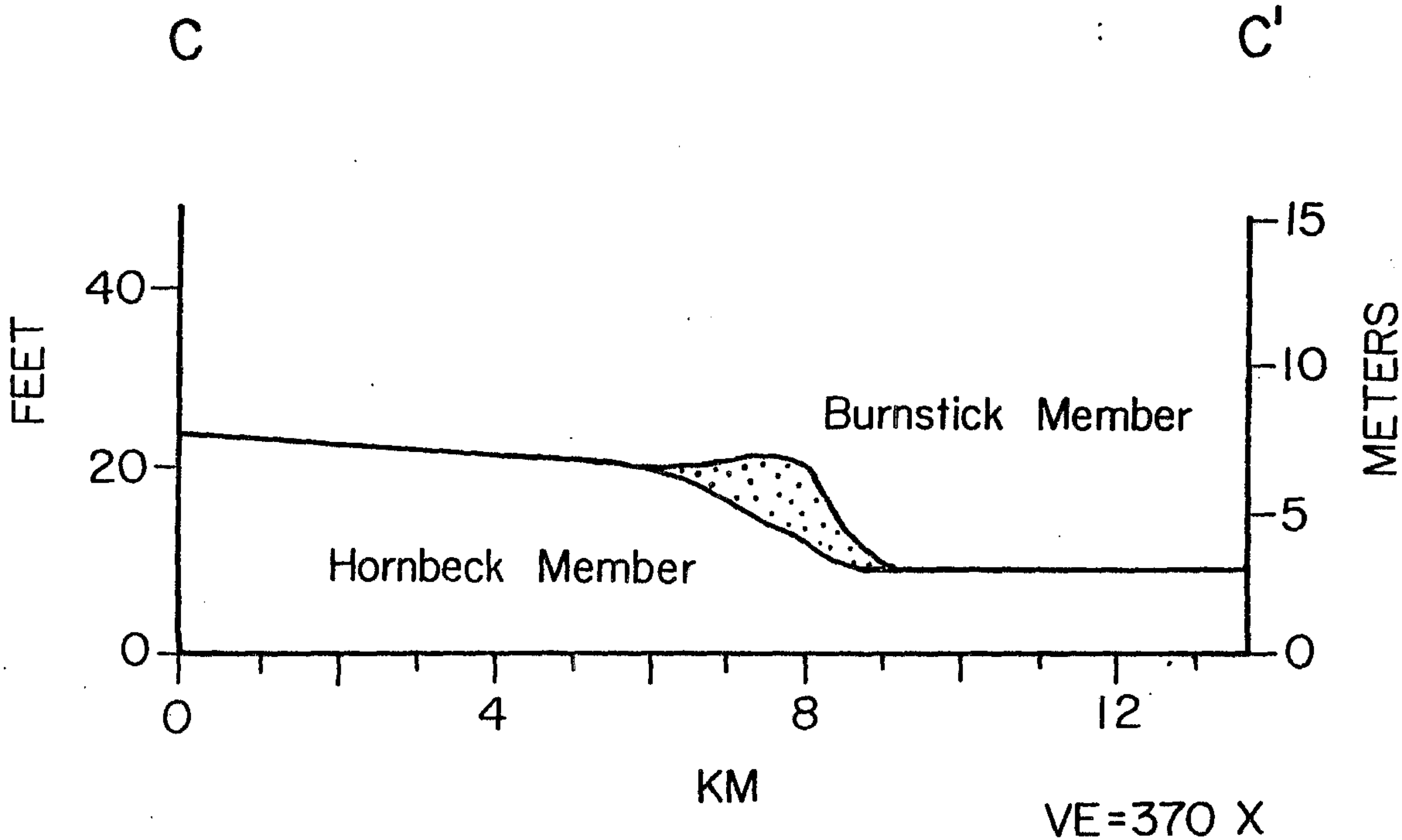

GARRINGTON
X
X
10
6
20
16
12
8
4
0
22
18
14
10
C
C'
C
C'
Y
Y
T36
5W5
T34
3W5
T32
T30
1W5
WELL LOG DATA
BURNSTICK MEMBER THICKNESS (feet)
BASE OF BURNSTICK TO LOWER MARKER (feet)
0
5
10
KILOMETERS

Figure 5.6. Cross section CC' from southern Garrington. This cross section shows the TB-BB isopach interval superimposed onto the BB-LM isopach interval. Note the localization of the Burnstick Member sediments on the dipping E4 surface.

GARRINGTON


C
C'
40
20
0
FEET
15
10
5
0
METERS
Burnstick Member
Hornbeck Member
0
4
8
12
KM
VE=370 X

Cross section CC' shows that the Burnstick Member sediments are localized on the dipping E4 surface (Figure 5.6). It is also interesting to note that the strike of the BB-LM isopach lines are parallel to the strike of the TB-BB isopach lines. This suggests that the three dimensional geometry of these two intervals are closely related.

5.5 Lochend Isopach Maps

Only 69 resistivity well logs were used to construct the two Lochend isopach maps due to the scattered concentration of data (Figure 5.7). Most of these data are located in the on-field area, with only a few data points from the off-field area. This makes it difficult to accurately identify the boundary of the Burnstick Member sediments or the off-field thickness of the BB-LM stratigraphic interval in Lochend.

The first isopach map (Figure 5.7) shows the thickness of the Burnstick Member (TB-BB). With the exception of a 14 foot thickness in T28/R3, the entire Lochend field has less than 12 feet of Burnstick Member sediments. It is difficult to identify any trends in the thickness of the Burnstick Member, due to the poor data base.

The distribution of the Burnstick Member sediments in Lochend outlines a long and narrow sandbody that is 55 kilometers long and 2.9 to 6.4 kilometers wide. This field is oriented in a NNW-SSE direction and has a strike of 333°.

Figure 5.7. The Burnstick Member thickness and the base of the Burnstick Member to the lower marker isopach maps for Lochend. The data base used to construct these two isopach maps is shown to the left.

The dashed isopach lines indicate the areas of poor well log control. Note the location of cross section DD' in central Lochend.

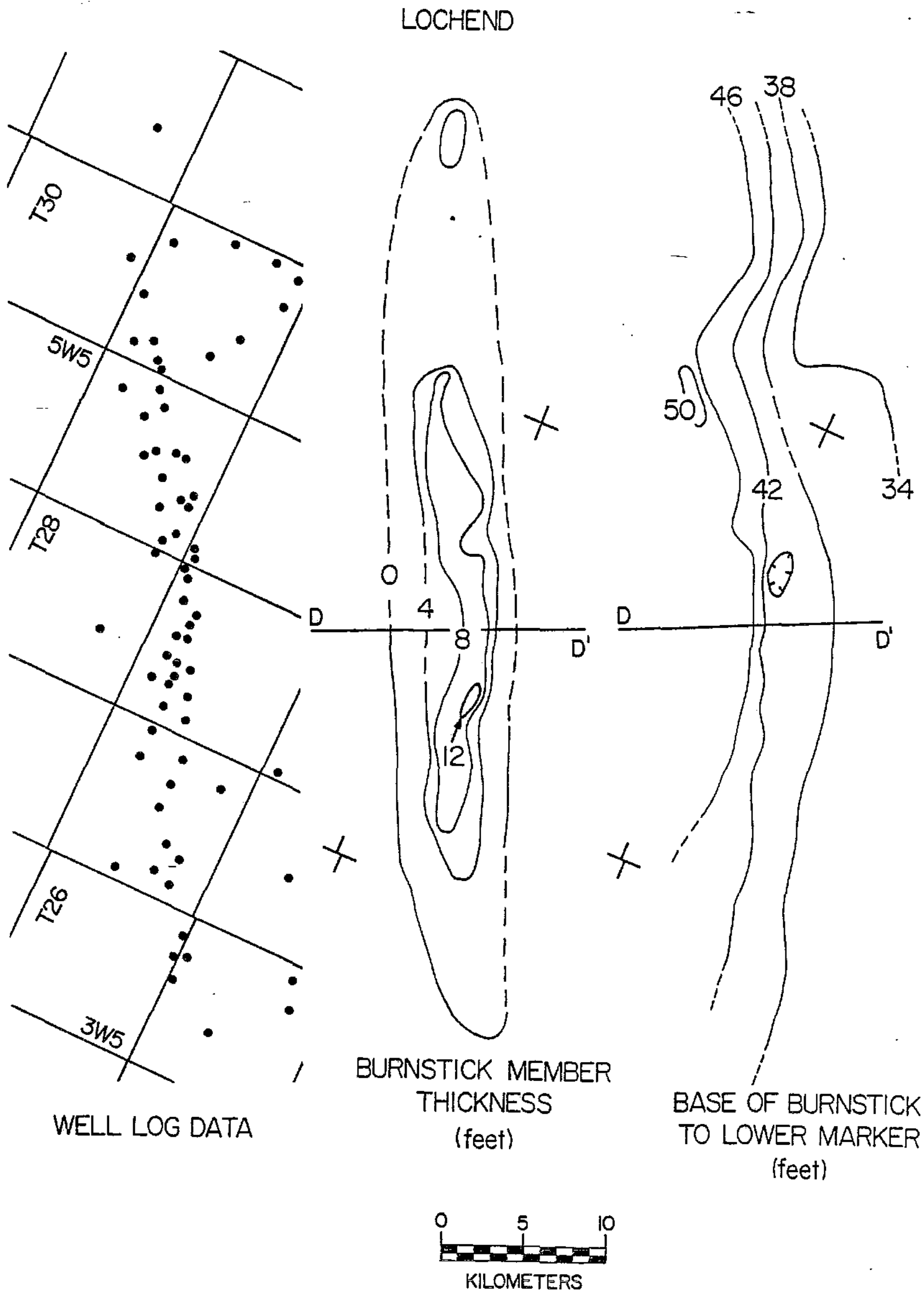
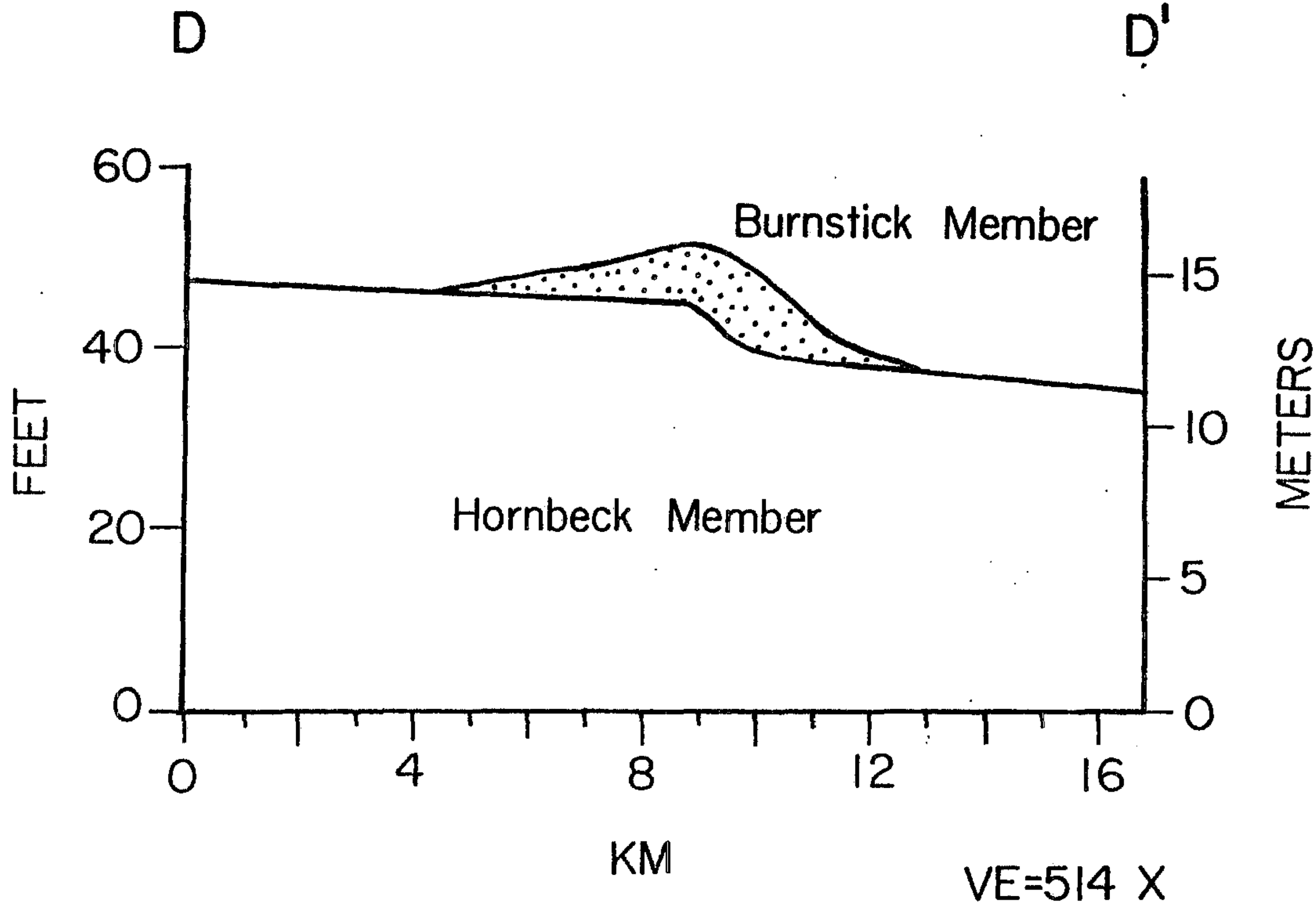

LOCHEND
T30
5W5
T28
T26
3W5
WELL LOG DATA
0
4
8
12
D
D'
BURNSTICK MEMBER
THICKNESS
(feet)
46
38
50
42
34
D
D'
BASE OF BURNSTICK
TO LOWER MARKER
(feet)
0
5
10
KILOMETERS

Figure 5.8. Cross section DD' from central Lochend. This cross section superimposes the data from the two isopach maps shown in Figure 5.7. Note the occurrence of the Burnstick Member sediments on the dipping E4 surface.

LOCHEND


D
D'
Burnstick Member
Hornbeck Member
60
40
20
0
FEET
15
10
5
0
METERS
0
4
8
12
16
KM
VE=514 X

Lochend is the shortest and the widest of the four Burnstick Member fields in the study area.

The second isopach map shows the thickness of the BB-LM stratigraphic interval. The BB-LM interval thins from 46-50 feet near the western edge of Lochend to 34 - 38 feet near the eastern edge (Figure 5.7). A drop of 8 to 12 feet is observed underneath Lochend, and defines a slope of 0.03° to 0.04° on the E4 surface. This trend is consistent with the trends observed underneath the other three Burnstick Member fields.

By superimposing two cross section lines from each isopach map it is possible to observe the relationship between the E4 surface and the overlying Burnstick Member sediments in Lochend (Section DD', Figure 5.8). The Burnstick Member sediments are concentrated on the dipping E4 surface in cross section DD' and rest at a stratigraphic interval lower than the off-field E4/T4 surface to the west. This relationship is consistently observed down the entire length of Lochend (Figure 5.7).

5.6 Similarities Between The Fields

By studying the thickness of the TB-BB and the BB-LM stratigraphic intervals for the four fields it is possible to observe the three dimensional sandbody geometry of the Burnstick Member, and the three dimensional geometry of the E4 surface. In each pair of isopach maps, the orientation of the Burnstick Member sediments and the strike of the E4 surface are parallel.

The most important similarities between the four fields are:

(1) the field dimensions are long and narrow with a length:width ratio greater than 10:1 (Figure 5.9);

(2) the average thickness of the Burnstick Member is between 2.3 meters to 4.0 meters (Figure 5.9);

(3) the strike of the fields varies from 318° (Caroline) to 339° (Crossfield) (Figure 5.9);

(4) the E4 surface dips to the northeast underneath the fields;

(5) the E4 surface rests stratigraphically higher to the west of the field than to the east of the field; and

(6) the Burnstick Member sediments are localized on the dipping part of the E4 surface.

Of these similarities, the last appears to be the most significant as it relates the three dimensional geometry of the Burnstick Member sediments to the underlying three dimensional topography of the E4 surface. The significance of this observation will be discussed in Chapter 7.

Field	Length	Width	Thickness	Strike
Caroline	72 km	3.6 km	4.0 m	318°
Crossfield	72	3.7	4.0	329-339
Garrington	90+	2.6	2.3	320
Lochend	55	4.4	3.3	333

Figure 5.9. The length, width, thickness and the strike of the four Burnstick Member fields in the study area. The width and the thickness of the fields are average values.

CHAPTER 6: Relationships Between the Four Fields

6.1 Introduction

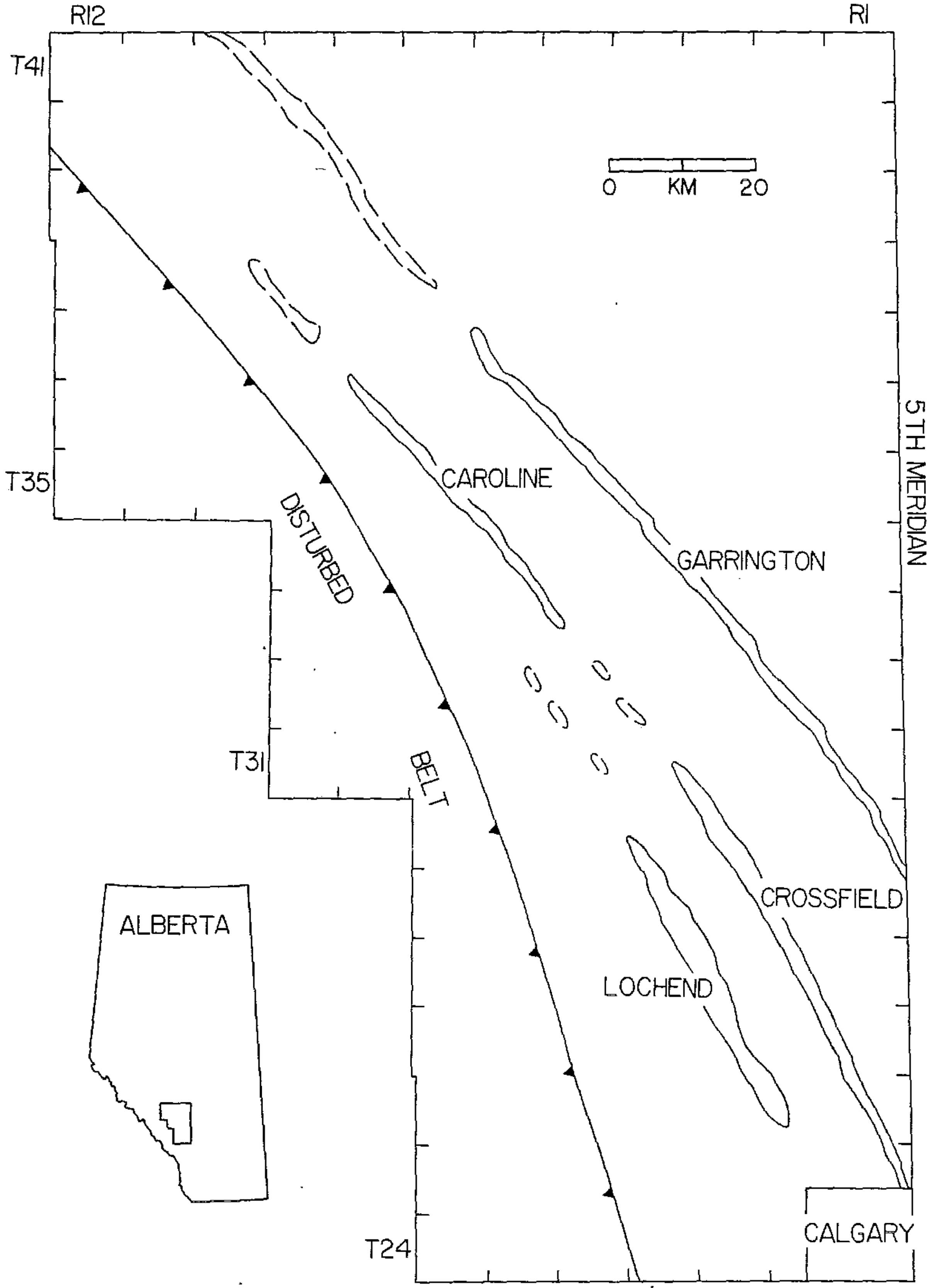
The purpose of this chapter is to relate the geometry of the Burnstick Member sediments and the E4 surface between the four fields. This is accomplished by studying the relationship between the four fields, parallel and perpendicular to the field strikes.

6.2 Parallel to the Field Strike

There are three long and linear Burnstick Member belts in the study area. These three belts can be identified by the strike of the Garrington field, the strikes of the Crossfield and the Caroline fields, and the strike of the Lochend field (Figure 6.1). Each one of these belts consists of Burnstick Member fields and Burnstick Member "pods". The Burnstick Member "pods" are delineated by well log data and are much smaller than the Burnstick Member fields.

The Garrington belt consists of the Burnstick Member in Garrington and a northwest extension of the Burnstick Member beneath the Ferrier field. The northwest extension of the Burnstick Member begins in T38/R7W5 and extends up to the northwest corner of the study area in T41/R10W5. The width,

Figure 6.1. The location of the four fields (solid lines) and the Burnstick Member "pods" (dashed lines). The "pods" are delineated by well log data and are on strike with the fields. Note the occurrence of three different Burnstick Member belts on strike with Garrington, Caroline/Crossfield and Lochend.


R12
R1
T41
T35
T31
T24
0 KM 20
5TH MERIDIAN
CAROLINE
GARRINGTON
DISTURBED
BELT
CROSSFIELD
LOCHEND
CALGARY
ALBERTA

thickness and strike of the Burnstick Member sediments in the northwest extension are similar to the Garrington field dimensions. These two Burnstick Member deposits line up to form a 145 kilometer long belt. Other than a 7 kilometer break in T37/R7W5, the Garrington belt is continuous throughout the entire length of the study area.

The Caroline/Crossfield belt consists of the Burnstick Member in Caroline and in Crossfield, and three Burnstick Member "pods". Two of the Burnstick Member "pods" are located between the two fields, while the third "pod" is located northwest of Caroline. The Caroline/Crossfield belt is approximately 150 kilometers long and extends from T38/R10W5 in the north to T25/R1W5 in the south.

The two Burnstick Member "pods" between Caroline and Crossfield are single well occurrences and consist of 6.0 feet in the southern "pod" (3-7-32-4W5) and 6.2 feet (7-26-32-5W5) in the northern "pod". The other Burnstick Member "pod" is located north of Caroline and consists of less than 6 feet of Burnstick Member, with the exception being 10-13-38-10W5 which contains 9.8 feet of Burnstick Member.

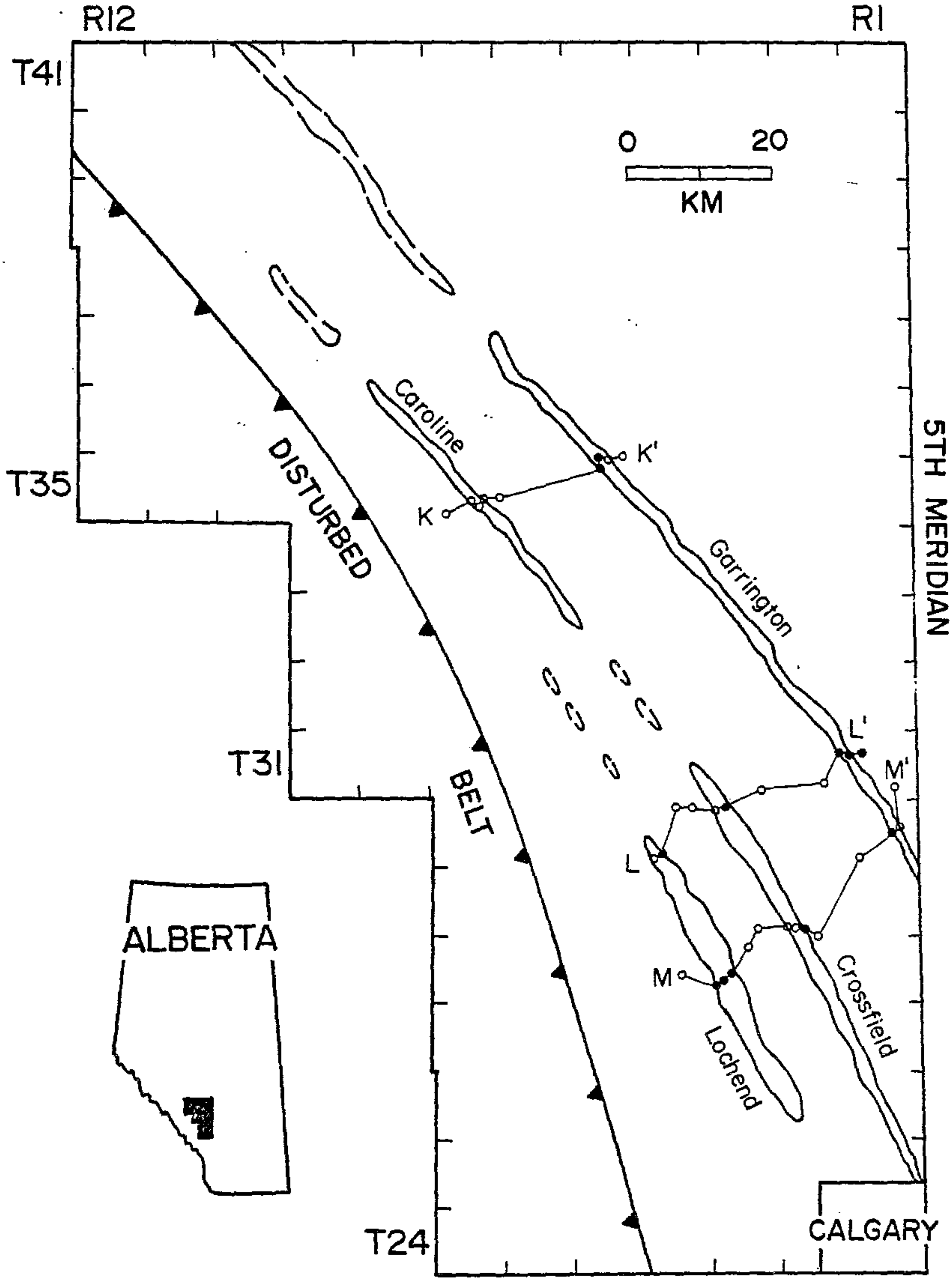
The third Burnstick Member belt occurs in the western part of the study area and consists of the Burnstick Member in Lochend and three Burnstick Member "pods". This belt is approximately 75 kilometers long and is oriented parallel to the other two belts in the study area. The three Burnstick Member "pods" are located northwest of Lochend and are defined by thin Burnstick Member deposits that are 2 to 3 meters thick. It is possible that a fourth Burnstick Member "pod" is observed northwest of Lochend in 10-11-35-8W5. However, the Burnstick Member deposit in 10-11-35-8W5 could be an off-field west deposit from Caroline rather than an on-field deposit parallel to Lochend.

The occurrence of the Burnstick Member in the study area outlines three long, linear and parallel belts. These belts can be traced up to 150 kilometers across the study area and are observed north of the study area in the Edson and the Pine Creek fields (Plint et al, 1986). The most striking characteristics of these belts include their long and linear dimensions, and the on-strike nature of the fields and "pods".

6.3 Perpendicular to the Field Strike

Three well log cross sections are constructed perpendicular to the strike of the Burnstick Member belts in order to relate the geometry of the Burnstick Member and the E4 surface. Two of the well log cross sections are constructed across Lochend, Crossfield and Caroline, while the third one is constructed across Caroline and Garrington (Figure 6.2). All three of the well log cross sections are hung on the lower marker (LM).

Figure 6.2. Location map for the three cross sections constructed perpendicular to the strike of the belts.


R12
R1
T41
T35
T31
T24
0
20
KM
5TH MERIDIAN
DISTURBED
BELT
Caroline
Garrington
Crossfield
Lochend
K
K'
L
L'
M
M'
ALBERTA
CALGARY

Cross Section KK'

Cross section KK' consists of 9 resistivity well logs from the Caroline-Garrington area and it covers a distance of 25 kilometers (Figure 6.3). The strike of cross section KK' is roughly perpendicular to the strike of the Garrington and the Caroline/Crossfield belts.

The stratigraphic interval between the upper marker (UM) and the lower marker (LM) brackets the occurrence of the Burnstick Member in Caroline and in Garrington. Well developed Burnstick Member deposits are observed in well logs 7-15-35-7W5, 4-14-35-7W5 and 10-14-35-7W5 from Caroline, and in well logs 11-34-35-5W5 and 16-34-35-5W5 from Garrington. The other four well logs are from the off-field west or from the off-field east areas and are characterized by weak Burnstick Member well log responses.

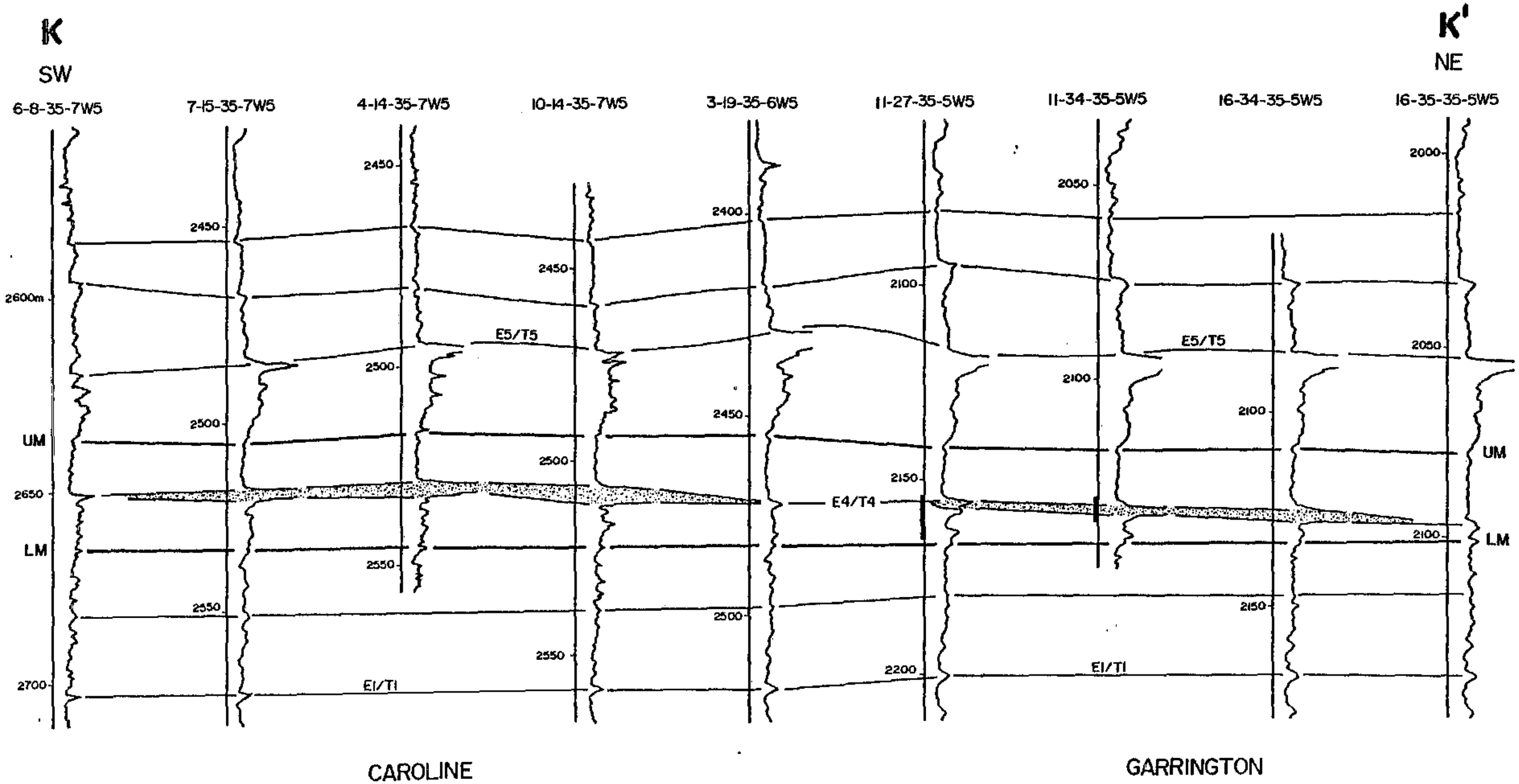
The most significant characteristics of cross section KK' are:

(1) the thinning of the UM-LM stratigraphic interval from the southwest to the northeast;

(2) the higher stratigraphic position of the Burnstick Member in Caroline than the Burnstick Member in Garrington; and

(3) the horizontal relationship between the base of the Burnstick Member in Caroline (3-19-35-6W5) and the top of the Burnstick Member in Garrington (11-27-35-5W5).

Figure 6.3. Cross section KK' constructed through Caroline and Garrington, located in Figure 6.2.



K
SW
K'
NE
6-8-35-7W5
7-15-35-7W5
4-14-35-7W5
10-14-35-7W5
3-19-35-6W5
11-27-35-5W5
11-34-35-5W5
16-34-35-5W5
16-35-35-5W5
2600m
2650
2700
UM
LM
E5/T5
E4/T4
E1/T1
CAROLINE
GARRINGTON

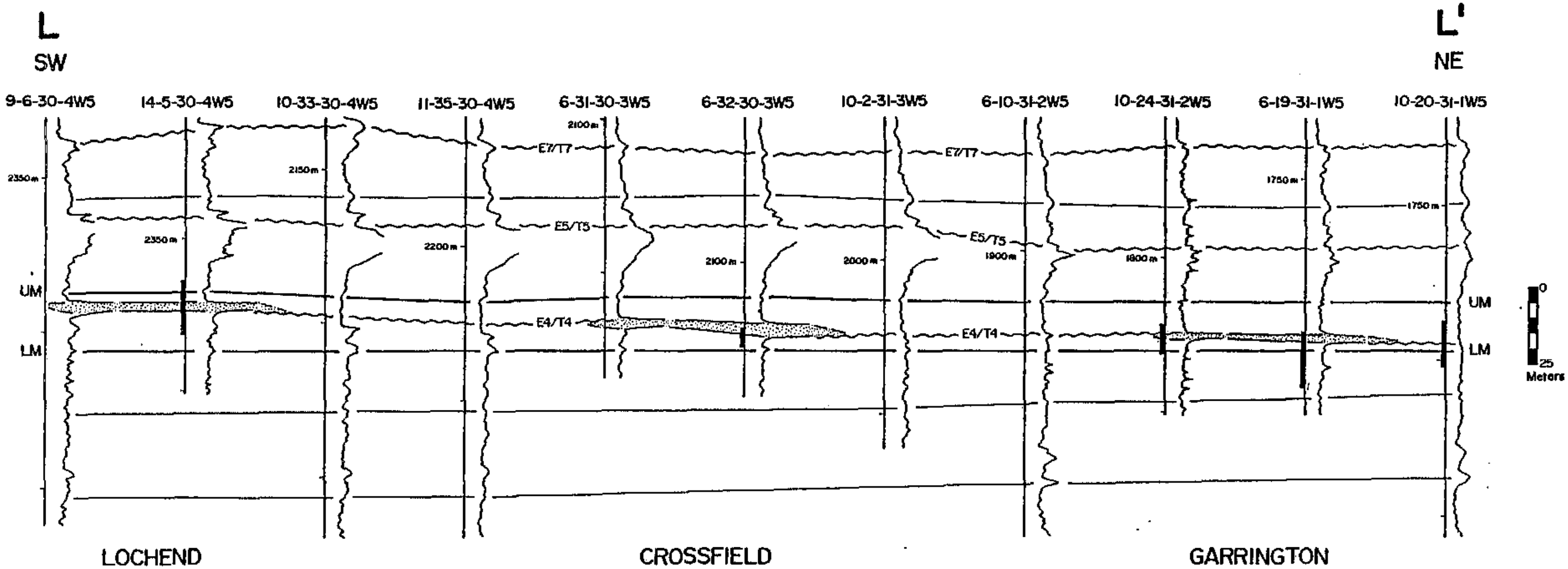
The latter two characteristics indicate that the Burnstick Member rests at two different stratigraphic positions. The Burnstick Member in Caroline rests mid way between the UM-LM interval, while the Burnstick Member in Garrington rests towards the base of the UM-LM interval. This defines a two dimensional step-like topography between the two Burnstick Member belts in cross section KK'.

Cross Section LL'

Cross section LL' consists of 11 resistivity well logs from northern Lochend, northern Crossfield, southern Garrington and the off-field areas in between (Figure 6.4). This cross section covers a distance of approximately 35 kilometers and is oriented perpendicular to the strike of the three fields. Six of the well logs in cross section LL' are from the on-field areas (2 per field), while the other five well logs are from the off-field areas.

Cross section LL' links the three Burnstick Member belts and shows the two dimensional geometry of the Burnstick Member and the E4 surface perpendicular to the strike of the fields. The stratigraphic interval between the upper marker (UM) and the lower marker (LM) is used to bracket the Burnstick Member sediments. It is interesting to note that the Burnstick Member sediments rest at three different stratigraphic intervals in cross section LL' (Figure 6.4). The highest occurrence of the Burnstick Member is in Lochend and

Figure 6.4. Cross section LL' constructed through Lochend, Crossfield and Garrington, located in Figure 6.2.



L
SW
L'
NE
9-6-30-4W5
14-5-30-4W5
10-33-30-4W5
11-35-30-4W5
6-31-30-3W5
6-32-30-3W5
10-2-31-3W5
6-10-31-2W5
10-24-31-2W5
6-19-31-1W5
10-20-31-1W5
E7/T7
E5/T5
E4/T4
UM
LM
2350m
2150m
2200m
2100m
2000m
1900m
1800m
1750m
0
25
Meters
LOCHEND
CROSSFIELD
GARRINGTON

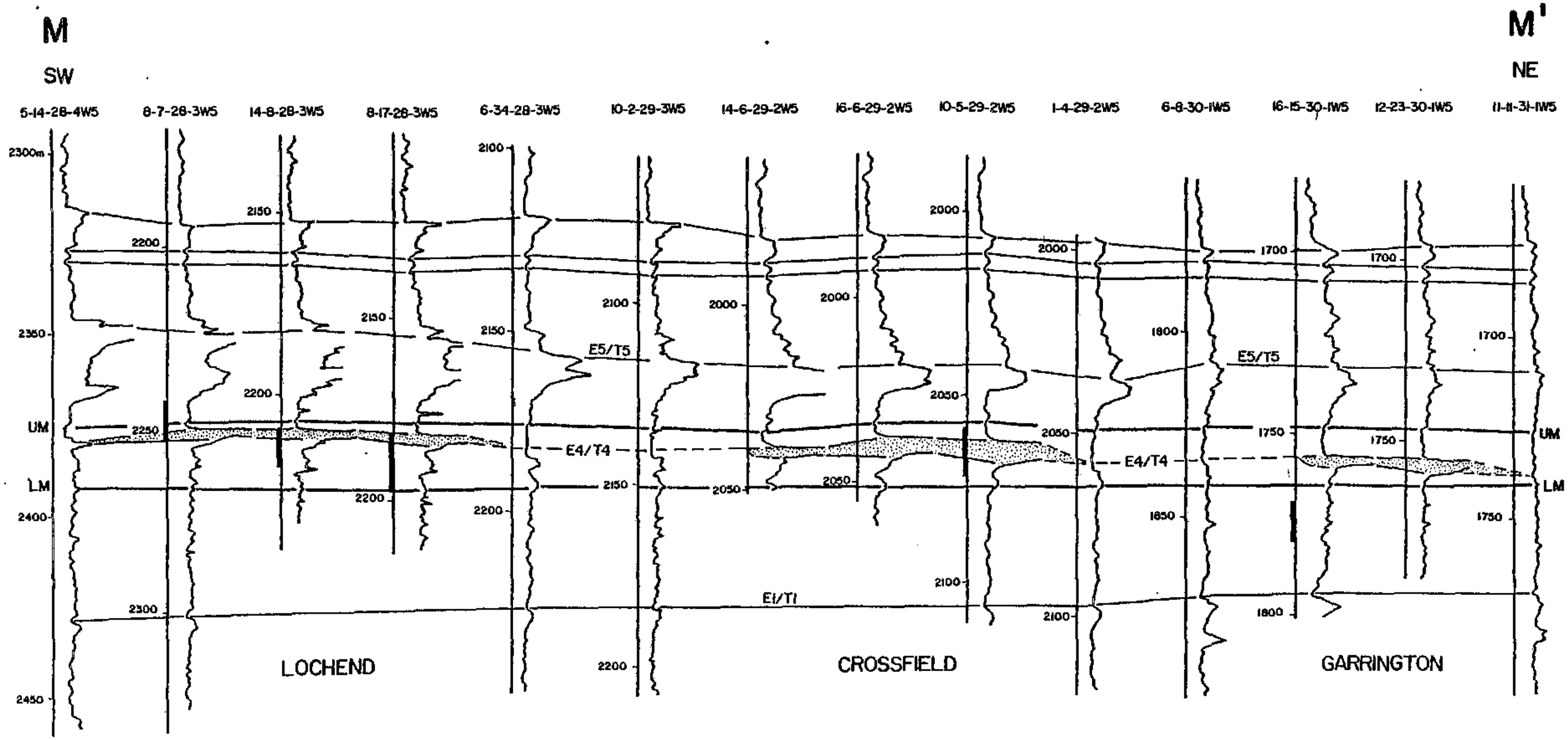
the lowest occurrence of the Burnstick Member is in Garrington. The three different Burnstick Member intervals outline a step-like topography that rises from the northeast (Garrington) to the southwest (Lochend) perpendicular to the strike of the fields.

Cross Section MM'

Cross section MM' consists of 14 resistivity well logs from central Lochend, central Crossfield, southern Garrington and the off-field areas in between (Figure 6.5). This cross section is approximately 45 kilometers long and it is oriented perpendicular to the strike of the three fields.

The two dimensional geometry of the Burnstick Member and the E4 surface is illustrated in cross section MM'. The Burnstick Member rests at three different stratigraphic intervals outlining a step-like topography. The highest occurrence of the Burnstick Member is in Lochend, while the lowest occurrence is in Garrington. From west to east the base of the Burnstick Member in Lochend passes into the top of the Burnstick Member in Crossfield, and the base of the Burnstick Member in Crossfield passes into the top of the Burnstick Member in Garrington. This step like topography is also observed in cross sections KK' and LL'.

Figure 6.5. Cross section MM' through Lochend, Crossfield and Garrington, located in Figure 6.2.


M
SW
M'
NE
5-14-28-4W5
8-7-28-3W5
14-8-28-3W5
8-17-28-3W5
6-34-28-3W5
10-2-29-3W5
14-6-29-2W5
16-6-29-2W5
10-5-29-2W5
1-4-29-2W5
6-8-30-1W5
16-15-30-1W5
12-23-30-1W5
11-11-31-1W5
E5/T5
E4/T4
E1/T1
UM
LM
LOCHEND
CROSSFIELD
GARRINGTON

6.4 Summary

Based on the evidence presented in the previous two sections, the Burnstick Member occurs in three long, linear and parallel belts in the study area. These three belts define a step like topography that steps up towards the west from the Garrington belt, to the Caroline/Crossfield belt up to the Lochend belt.

CHAPTER 7: Interpretation

7.1 Introduction

The purpose of this chapter is to interpret the environment of deposition of the Burnstick Member. The order in which the interpretations are developed coincides with the depositional history of the sediments.

The sequence of interpretation in this chapter is as follows: (1) the Hornbeck Member facies, (2) the E4 surface, (3) the Burnstick Member facies, (4) the T4 surface, (5) the lower Raven River Member facies and, (6) the sediment supply mechanism. Where appropriate, the sequence of events leading to the development of these features in all three Burnstick Member belts will be discussed.

7.2 Hornbeck Member Deposition

Facies 1A and 2A are the two facies observed in the Hornbeck Member within the study area. Both of these facies consist of dark silty mudstone, with the latter (facies 2A) being more silty than the former (facies 1A). These facies contain sharp based silt beds or laminae that are rarely wave rippled.

Walker (1983c) sampled the foraminiferal fauna of these facies in Garrington and it was suggested by C. Mahadeo (in Walker, 1983c) that they were deposited in a "coastal subaqueous" (20 - 50 m water depth) to a "shallow marine" (> 50 m water depth) environment, with depth estimates from foraminiferal ecology. This suggests that the silt laminae and beds were deposited by bottom currents in relatively deep water, well below fairweather wave base. The "quiet water" deposition of the Hornbeck Member facies is indicated by the abundance of mud and by the absence of ubiquitous wave ripples in the silt laminae and beds.

7.3 Development of the E4 Surface

The E4 surface underlies the Burnstick Member sediments, and forms the contact between the Hornbeck and Burnstick Members. This surface was identified throughout the study area on the detailed well log and core cross sections (Chapter 4), and from BB-LM isopach maps (Chapter 5). The sharpness of this contact was discussed in Chapter 3.

(A). Is the E4 Surface Erosional?

In considering the nature of the E4 surface it is important to observe its geometry underneath and between the four fields. The first part of this discussion will concentrate on the geometry of the E4 surface underneath the four fields while the second part will focus in on the geometry of the E4 surface between the four fields.

(i) E4 Surface Underneath the Fields

The geometry of the E4 surface is consistently observed to dip or drop down towards the NE outlining a sigmoidal or S - shaped scour underneath each of the four fields. This indicates that the Hornbeck Member facies become thinner from the SW to the NE beneath the four fields. In Crossfield, up to 6 meters of Hornbeck Member sediments are missing or "cut out" on the eastern side of the field. This seems to suggest that the Hornbeck Member was eroded during the development of the E4 surface.

Due to the lack of a vertical facies sequence in the upper Hornbeck Member, it is difficult to prove that the overlying E4 surface is erosive based on the observed sequence of upper Hornbeck Member facies. Unlike the E5 surface at Carrot Creek, Pembina and Ferrier, which erodes into a distinctive set of coarsening upward facies (Bergman, 1987; Leggitt, 1987; McLean, 1987), the E4 surface erodes into two similar, deep marine facies (facies 1A and 2A). This made it very difficult to identify the geometry of the E4 surface and created the need for an identifiable, correlatable, lower marker below the E4 surface. Once this marker was established, it allowed for the construction of the well log cross sections, core cross sections and the BB-LM isopach maps for the four fields (Chapters 4, 5 and 6). All of these illustrations indicate that the Hornbeck Member becomes thinner towards the northeast underneath each of the four fields. This is interpreted to result from the erosion of the Hornbeck Member sediments during the development of the E4 surface.

Further proof of erosion at the E4 surface comes from the sedimentological evidence at the Hornbeck/Burnstick Member contact. Granules and pebbles are often observed in the lower one third of facies 6 (lower most Burnstick Member facies) which is in contrast to the deep marine mudstones of the Hornbeck Member below. Rare ripped up mud clasts are also observed in the lower one third of facies 6. Both of these observations suggest that there was a period of erosion before the deposition of the Burnstick Member, producing a lag deposit of granules, pebbles and mud clasts. This period of erosion coincides with the development of the E4 surface.

By combining the data from well log cross sections, core cross sections, BB-LM isopach maps of the E4 surface, and the sedimentology of the Hornbeck/Burnstick Member contact, it becomes apparent that the E4 surface is erosional underneath each of the four fields.

(ii) E4 Surface Between the Fields

In contrast to the scour - like geometry of the E4 surface underneath the four fields, the E4 surface between the four fields remains relatively flat and is coplanar with the T4 surface (Figures 6.3, 6.4 and 6.5). Hence, this surface is labelled as the E4/T4 surface. It is difficult to identify the E4/T4 surface in all the areas between the four fields. Most occurrences of the E4/T4 surface are observed within 5 km of the western field boundary and within 2 km of the eastern field boundary around each of the four fields.

Figures 6.3, 6.4 and 6.5 show that the E4/T4 surface can be identified on the resistivity well logs as a small rightwards deflection. The E4/T4 surface outlines a horizontal plane between the fields and, along with the scour - like geometry of the E4 surface underneath the fields, produces a step - like geometry across the study area (Figures 6.3, 6.4 and 6.5).

It is difficult to determine if the E4/T4 surface is erosive between the four fields because it is parallel to the lower marker. It is possible that the E4/T4 surface is erosive and that the Hornbeck Member sediments have been eroded to an equal depth between the fields. This would explain why the E4/T4 surface is parallel to the lower marker in between the four fields.

(B). Subaerial, Submarine or Shoreface Erosion?

The next question to ask is how did the proposed erosion of the E4 surface occur? There are only three environments in which the E4 surface could have formed; fully subaerial, fully submarine, or in between at the shoreface. Each one of these possibilities will be considered separately in order to determine the most probable environment of erosion. Similar arguments have been proposed by Bergman (1987), Leggitt (1987) and McLean (1987) in order to explain the development of the E5 surface.

Before continuing with the discussion of the environment of erosion it is important to review the geometry of the E4 surface throughout the study area. The following facts have been established through the study of the E4 surface in well log cross sections (Chapters 4 and 6), core cross sections (Chapter 4) and isopach maps (Chapter 5):

(1) The E4 surface is horizontal and co-planar with the T4 surface between the fields and is incised underneath the four fields. Therefore, the E4 surface is observed throughout a large part of the study area.

(2) The incised E4 surfaces line up to form three straight belts throughout the study area. These three belts line up with the Garrington, Caroline -- Crossfield and Lochend fields respectively.

(3) The three incised E4 surface belts have similar geometries outlining a one sided scour open towards the northeast.

(4) The depth of erosion in the incised belts is between 2 - 6 m.

(5) The incised E4 surface belts underneath the four fields and the horizontal E4/T4 surface between the four fields combine to form a step - like topography across the study area that "steps up" towards the southwest.

(6) The closest time equivalent paleoshoreline to the E4 surface is observed in the Kakwa Member. The Kakwa Member

has been studied by Plint and Walker (1986) in the subsurface Cardium Formation of southern Alberta and is interpreted to be a shoreface deposit. The incised E4 surface belts are at least 100 km east of the closest known Kakwa Member and are oriented parallel to the trend of the Kakwa shoreface (Figure 2.1).

When determining the environment of erosion for the E4 surface it will be important that the interpretation is consistent with the six facts presented above.

(i) Subaerial Environment

The first environment to be considered for the cutting of the E4 surface is a fully subaerial setting. In this environment the E4 surface would probably be cut by fluvial processes as there are no other processes that could explain the long and narrow characteristics of the E4 surface.

Four outstanding problems exist if the E4 surface is considered to have developed in a fully subaerial (fluvial) environment. Most of these problems are related to the differences between the expected geometry of a fluvial system and the observed geometry of the E4 surface.

The first problem involves the plan view geometry of the incised E4 surface belts. Figures 5.1, 5.3, 5.5, and 5.7 show that the incised E4 surfaces are very long and narrow. This is especially evident in Figures 5.3 and 5.5 from Crossfield and Garrington. If these incised E4 surfaces were a result of fluvial erosion the belts would not be as straight and it is probable that tributaries would be observed close to the main trend. In this sense, the plan view geometry of the incised E4 surfaces do not resemble a fluvial system.

The second problem with a fluvial interpretation is the cross sectional geometry of the incised E4 surfaces. All four incised E4 surfaces outline a one - sided scour that is open towards the northeast. If the cutting of the incised E4 surface was a result of fluvial processses, a two - sided channel would probably be preserved. However, in each of the four fields, only one side of the incised E4 surface is observed and hence, it is unlikely that the incised E4 surface is a fluvial channel. Further support for this idea comes from the fact that the E4 surface is observed throughout the study area as a horizontal plane (in between the fields) or as an incised belt (underneath the fields). Fluvial erosion could not explain the development of the E4 surface throughout the entire study area.

The third problem with a fluvial interpretation involves the orientation of the incised E4 surface belts relative to the closest known paleoshoreline. As mentioned in the beginning of this section, the Kakwa Member represents the closest time equivalent paleoshoreline to the Burnstick Member and is roughly parallel to the strike of the incised E4 surface trends (Figure 2.1). This suggests that the incised E4 surface belts were cut parallel to the regional tectonic trend or perpendicular to the paleoslope dip direction. Most if not all fluvial systems flow parallel to the regional paleoslope dip direction which is roughly 90° away from the orientation of the incised E4 surface belts. If the incised E4 surface belts were produced by fluvial erosion it is most likely that they would be oriented SW - NE and not NW - SE.

The fourth and final problem with a fluvial interpretation are the sediments that rest against the incised E4 surface belts. The Burnstick Member sediments form a marine, coarsening upward vertical facies sequence that is localized within the one - sided scour of the E4 surface. These sediments do not bear any resemblance to a fining upward facies sequence that is expected in a fluvial environment.

Based on the four outstanding problems presented above it is possible to exclude a fluvial origin for the development of the E4 surface. This leaves two other potential environments including a submarine or a shoreface setting.

(ii) Submarine Environment

The second possible environment in which the E4 surface could have developed is in a fully submarine setting. In this setting, it is possible that the E4 surface would have been cut by marine processes such as storm wave scour, turbidity currents or density currents. Erosion in a fully submarine setting can be either shallow, broad, storm wave scour or focussed channelized erosion. Both types of submarine erosion will be considered in this discussion.

Many problems are encountered when attempting to explain the development of the E4 surface in a fully submarine environment. These problems have been condensed into three major points.

The first problem with the cutting of the E4 surface in a submarine environment involves the depth of erosion associated with marine processes. Two main types of marine erosion occur including shallow, broad storm wave scours and deeper, localized submarine channels. The shallow broad storm wave scours have been interpreted to scour the nearshore sand bottom to a depth of approximately 2 meters (Kumar and Sanders, 1976). In contrast, the deeper submarine channels can be 5 - 600 m deep as indicated by the channels in the Amazon submarine fan (Damuth and Flood, 1985). This highlights a more localized and a deeper form of submarine erosion.

The erosion of the E4 surface appears to be widespread throughout the study area with three localized, incised E4 surface belts superimposed on the much broader, horizontal E4/T4 surface. The depth of erosion for the E4 surface is between 2 - 6 m in the incised belts and is unknown in the areas between the fields. This pattern of erosion seems to be inconsistent with the shallow, storm wave scours identified by Kumar and Sanders (1976) and is also inconsistent with the deep, localized submarine channel or canyon erosion. Neither type of erosion can fully explain the basin wide development of the E4 surface.

The second problem for a fully submarine development of the E4 surface involves the geometry and orientation of the three incised E4 surface belts. It has been established that the incised E4 surface belts are very straight (plan view), have a one - sided scour geometry open towards the NE (cross sectional view), and have a strike perpendicular to the paleoslope dip direction. All three of these facts are inconsistent with the probable geometry and orientation of a submarine channel or canyon. If the incised E4 surface belts were submarine channels the following characteristics would be expected; channel meanders or braids, a two sided channel geometry and an orientation parallel to the paleo-slope dip direction. None of these features are observed for the E4 surface suggesting that the submarine development of the E4 surface is improbable.

The third problem with a fully submarine origin for the E4 surface involves the sediments that rest within the incised E4 surface belts. These Burnstick Member sediments are a coarsening upward, marine facies sequence and are unlike the channel and turbidite facies expected in a fully submarine setting.

It can be concluded that a fully submarine setting does not account for the geometry, orientation, depth of erosion and the sediments of the E4 surface. This leaves the shore-face setting as the only environment that might explain the development of the E4 surface.

(iii) Shoreface Environment

A shoreface is defined as the area seaward of a barrier from the low tide mark to the depth of fairweather wave base (Reinson, 1984). Modern shorefaces are characterized by a one sided scour geometry "open" towards the sea, a strike that is parallel to the shoreline and a dip of 0.03° - 0.30° perpendicular to the shoreline (Swift and Niedoroda, 1985).

In this section the hypothesis that the E4 surface is an incised shoreface will be tested. This will be accomplished by discussing six characteristics of the E4 surface and comparing these features to examples from modern shoreface environments.

(1) Plan view geometry of the incised E4 surface belts.

The three incised E4 surface belts in the study area are extremely long and straight and are traceable for up to 150 km. The length and the straightness of the incised E4 surface belts are consistent with various modern shorefaces. For example, there is a gently curving barrier island chain that extends for over 320 km along the Texas coast (Hill and Hunter, 1976) and includes the 177 km long Padre Island. Another example of a long and straight shoreface is the Long Island barrier island system which is over 160 km long (Rampino and Sanders, 1980). Both of these examples indicate that a shoreface can be extremely long and relatively straight. This is consistent with the observations of the E4 surface.

(2) Cross sectional geometry of the incised E4 surface belts.

All three incised E4 surface belts have a similar one-sided scour geometry perpendicular to the strike of the belts. In cross section, the southwestern part of each belt rests at a higher stratigraphic interval than the northeastern part (Figures 5.1, 5.3, 5.5 and 5.7). This outlines a stepping down or a drop in the E4 surface underneath the four fields.

In modern coastal environments the outline or cross sectional profile of the shoreface is similar to the profile produced by the E4 surface. Modern examples of shoreface profiles are shown by Swift (1975) and Swift and Niedoroda (1985). These profiles show a dropping down or a one-sided scour geometry that is open towards the sea. This is consistent with the observations of the E4 surface in the study area and lends support to the hypothesis that the E4 surface is an incised shoreface.

(3) Dips of the incised E4 surface belts.

By measuring the dip of the E4 surface underneath the four fields it will be possible to make direct comparisons to the dips of modern shorefaces. This will provide a further test to the hypothesis that the E4 surface is an incised shoreface.

The dip of the E4 surface is measured relative to the horizontal lower marker on the four isopach maps in Figures 5.1, 5.3, 5.5, and 5.7. Two assumptions are made in order to obtain a dip measurement, namely that the lower marker forms a horizontal plane, and that the lower marker plane does not dip into the basin. The first assumption is reasonable and necessary while the second assumption is inaccurate. It is reasonable to assume that the sediments of the lower marker dipped into the basin, however it is impossible to determine the magnitude of the dip. Therefore, it is necessary to use both assumptions when calculating the dip of the E4 surface. All of the E4 surface dip measurements will represent minimum values and in order to obtain an accurate dip would have to be added to the dip of the lower marker.

The dips of the incised E4 surface belts were calculated for the four fields and they show a range between 0.03°-0.11° NE (Figure 7.1). The steepest dip is observed in Crossfield, while the shallowest dip is observed in Caroline.

When comparing the dips on the E4 surface to those measured in the modern shoreface environment, a remarkable similarity exists. Swift and Niedoroda (1985) state that modern shorefaces dip between 0.029° - 0.29° seaward, while Reineck and Singh (1972) report a dip of 0.043° on the southern North Sea shelf, and Swift and Field (1981) record a 0.03° dip on the Maryland inner shelf and a 0.30° dip on the bar crest. Both the modern shoreface and shelf dips are consistent with the dip on the incised E4 surface belts. This supports the hypothesis that the E4 surface belts are incised shorefaces.

Field	Dip of the E4 Surface
Caroline	0.03 - 0.05°
Crossfield	0.08 - 0.11°
Garrington	0.04 - 0.08°
Lochend	0.03 - 0.04°

Figure 7.1. Measured dips of the E4 surface underneath the four fields. The dip measurements are made relative to a horizontal lower marker (LM) and are measured from the BB-LM isopach maps (Figures 5.1, 5.3, 5.5, and 5.7).

(4) Orientation of the incised E4 surface belts.

All three incised E4 surface belts are oriented in a NNW to SSE direction and are parallel to one another. The strike of these belts roughly coincides with the strike of the progradational limit of the Kakwa Member, Cardium Formation, north of Township 40 (Figure 2.1). Plint and Walker (1986) identified the Kakwa Member as a shoreface sequence and traced its occurrence throughout the subsurface of Alberta. The Kakwa Member represents the closest time equivalent shoreface sequence to the incised E4 surface belts.

Given that the incised E4 surface belts and the Kakwa shoreface are oriented parallel to each other, it seems likely that the incised E4 surface belts were cut perpendicular to the paleoslope dip direction. This is based on the assumption that the Kakwa shoreface was deposited perpendicular to the paleoslope dip direction. Thus, the orientation of the incised E4 surface belts also suggests an origin in a shoreface environment.

(5) Sediments against the incised E4 surface belts.

The Burnstick Member sediments rest within the incised E4 surface belts and form a coarsening upward, vertical facies sequence. These sediments are interpreted to be a marine coarsening upward sequence that consists of lower and middle shoreface sediments (Section 7.4A). The interpretation of the Burnstick Member sediments is consistent with the interpretation of the incised E4 surface belts and provides added evidence that the E4 surface developed in a shoreface environment.

(6) The horizontal E4/T4 surface.

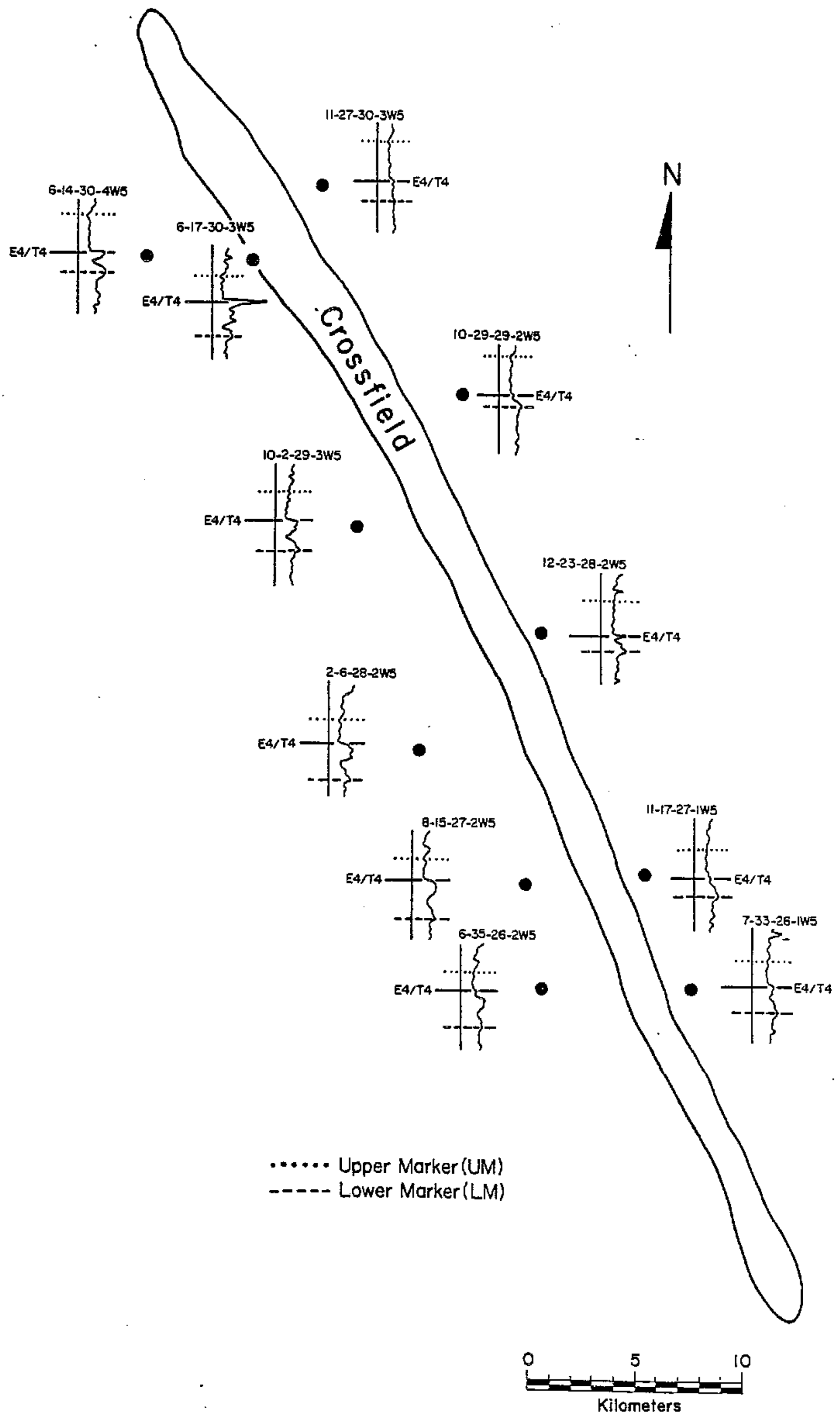
It has been established previously that the E4/T4 surface forms a "horizontal plane" relative to a lower marker in between the fields (Figures 6.3, 6.4 and 6.5). The E4/T4 surface planes can not be traced continuously in between the fields and are best developed within 5 km of the western field boundaries.

Given the previous five points in this discussion it is most likely that the incised E4 surface belts are shoreface profiles. This leaves the question of the environment of origin for the E4/T4 surfaces. A fully subaerial or a fully submarine setting could not account for the development of the E4/T4 surface as this surface is not channelized (fluvial or submarine) and does not exhibit the patchy, storm wave scour expected in a fully submarine environment. Once again this leaves a shoreface environment as the probable setting for the development of the E4/T4 surface.

A pebbly veneer of sediments rests on top of the E4/T4 surface and forms a sharp contact with the deep marine Hornbeck Member sediments below. On the western edges of the four fields the E4/T4 surface rests at a higher stratigraphic interval than the incised E4 surface underneath the fields. It is in this position where the E4/T4 surface is best developed (Figure 7.2).

Figure 7.2. A comparison of the resistivity well log signatures for the E4/T4 surface on the western and eastern boundaries of Crossfield. The E4/T4 surface on the west of Crossfield rests at a higher stratigraphic interval than on the east. This is typical for each of the four fields.

E4/T4 Well Log Signatures



In order to properly interpret the environment of formation for the E4/T4 surface it is necessary to consider its relationship with the incised E4 surface belts. The three incised E4 surface belts have been interpreted to be incised shorefaces. Only one shoreface could be developed or cut at any one time which suggests that sea level changes would be required to move the position of the shoreface from one belt to the next. During the rises in sea level it is possible that some of the sediments were reworked from the shoreface towards the west producing the pebbly veneer of the E4/T4 surface. It is also probable that wave action would scour the area between the fields during the rise in sea level. Both of these processes would combine to produce an identifiable E4/T4 surface. This will be discussed in more detail in the following section (7.3C).

Based on the evidence presented above, the E4 surface seems to have developed in a shoreface environment. This interpretation is based on a comparison of the geometry, orientation, dip and sediments of the incised E4 surface belts, with those of modern shoreface environments. Good correlations exist between the ancient environment (E4 surface) and its modern counterparts. The next section will examine the relationship between the three incised E4 surface belts (shorefaces) and the E4/T4 surface in between. This will be necessary in order to get a better understanding of how the E4 surface developed throughout the study area.

(C). Basinwide Development

It is most probable that the three incised E4 surface belts developed in a shoreface environment. In order for shoreface erosion to occur at the position of the three incised E4 surface belts it is necessary that the shoreface migrated from its previous position, tens of kilometers west of the belts (Kakwa shoreface), to a position at or seaward of the Garrington E4 surface belt. Subsequent rises in sea level would be responsible for moving the shoreface from one incised E4 surface belt to the next. In this manner it would be possible to erode the three incised E4 shorefaces in the study area. No other mechanism other than sea level fluctuations can sufficiently explain the development of the three incised E4 shorefaces within the study area. It is also probable that the E4/T4 surface was cut between the fields during the rises in sea level. This would explain how the E4 surface developed throughout the study area.

(i) General Sequence of Events

In order to acquire a better understanding of the development of the three E4 surface belts it will be necessary to divide the overall development into a sequence of events. By doing this, a step by step chronology of events will be established.

It is most likely that the Garrington E4 surface belt developed first because it is the most easterly of the three belts. If one of the other two belts developed first, the chances of preserving that belt during a further lowering of sea level would be remote. The following is a sequence of events interpreted from the observations of the E4 and the E4/T4 surfaces in the study area;

(1) Sea level dropped causing the shoreface to move from the eastern limit of progradation of the Kakwa Member to a position at or seaward of the Garrington belt.

(2) A shoreface was incised along the Garrington belt producing the E4 surface at Garrington. This occured during a stillstand.

(3) Sea level rose over top of the Garrington belt creating the E4/T4 surface west of Garrington.

(4) Sea level stabilized at a position at or seaward of the Caroline - Crossfield belt.

(5) A shoreface was incised along the Caroline - Crossfield belt producing the incised E4 surface at Caroline and Crossfield. This occured during a stillstand.

(6) Sea level rose over top of the Caroline - Crossfield belt creating the E4/T4 surface to the west of the belt.

(7) Sea level stabilized at a position at or seaward of the Lochend belt.

(8) A shoreface was incised along the Lochend belt producing the incised E4 surface at Lochend. This occured during a stillstand.

(9) Sea level rose over top of the Lochend belt producing the E4/T4 surface west of this belt.

Direct evidence for sea level fluctuations can be interpreted from the positions of the three incised E4 surface belts. Shoreface profiles can only be formed in a very restricted part of the coastal environment forming a narrow geomorphic feature in relation to the surrounding shelf environment. By observing more than one shoreface profile in the study area it is possible to conclude that sea level changes caused the migration of the shoreface throughout the basin. The magnitude of these sea level changes will be discussed in Section 7.3C(ii).

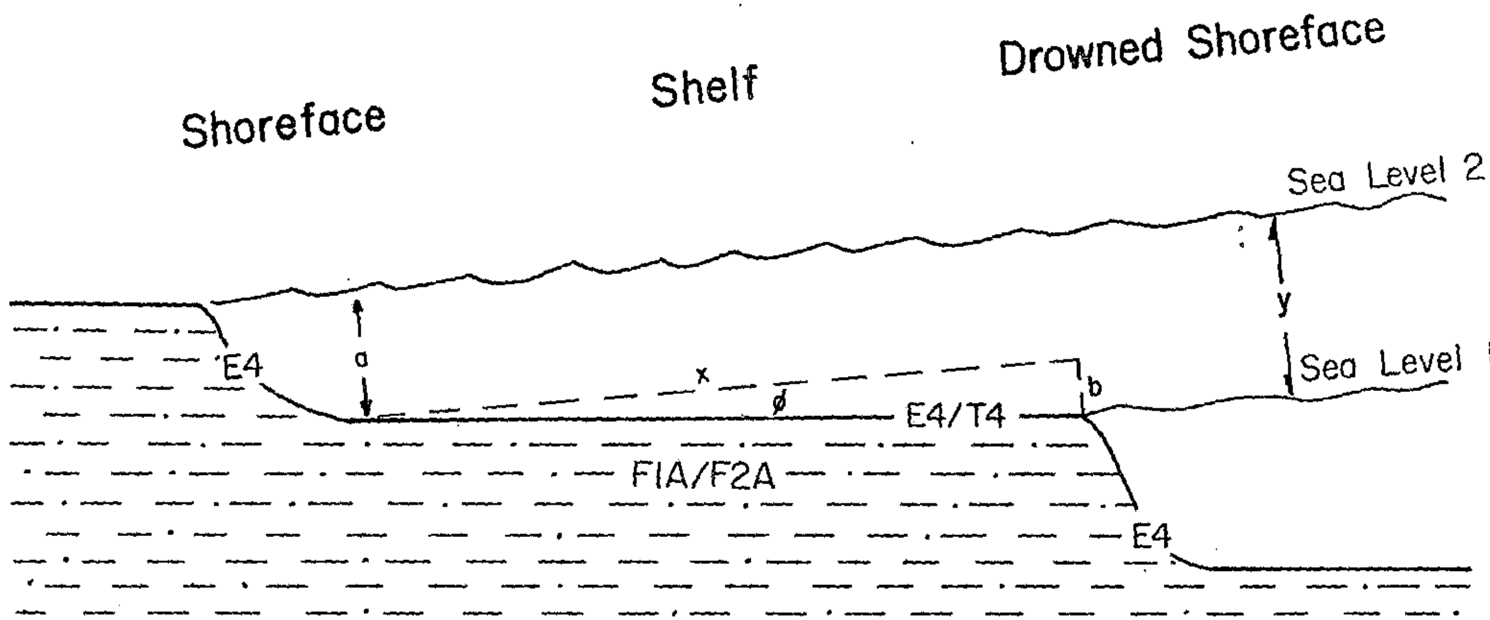
(ii) Calculated Sea Level Rises

One measured value and two assumed values are used to calculate the magnitude of sea level changes required to move the shoreface from one belt to the next (Figures 7.3 and 7.4). Due to the inaccuracies involved with assuming a dip on the Cretaceous shelf and a height of the Burnstick Member shoreface, it is only possible to get a "ballpark" estimate of the sea level rises. Figure 7.3 shows the method used for calculating the sea level rises and Figure 7.4 tabulates the results from the assumptions and calculations.

A sea level rise of 25.8 ± 13.2 m is believed to have moved the shoreface from the Garrington to the Caroline-Crossfield belt, while a sea level rise of 19.4 ± 10.0 m was responsible for moving the shoreface from the Caroline-Crossfield to the Lochend belt. The sea level changes necessary to move the shoreface from the Kakwa Member to the Garrington belt, and from the Lochend belt further to the

Figure 7.3. The method used for calculating the amount of sea level rise necessary to move the shoreface from one belt to the next (Sea Level 1 to 2). x - horizontal distance between two adjacent belts, ϕ - assumed dip of the shelf, b- height separating the "toe" and the "head" of two adjacent belts, a - assumed height of the shoreface, y - amount of sea level rise, F1A/F2A - facies 1A and 2A. This figure is vertically exaggerated.

See Figure 7.4 for the calculated sea level rises from Garrington to Caroline/Crossfield, and from Caroline/Crossfield to Lochend.



$$b = (\tan \phi)\, x$$

$$\text{Sea Level Rise } (y) = a + b$$

	C/C - G Belts	L - C/C Belts
Average Distance (x)	15.3 ± 1.1 km	8.9 ± 0.8 km
Assumed Shelf Dip (b/x)[1]	0.001 ± 0.0005	0.001 ± 0.0005
Assumed Shelf Dip (ϕ)	0.057 ± 0.029°	0.057 ± 0.029°
(tan ϕ)x = (b)	15.3 ± 7.7 m	8.9 ± 4.5 m
Shoreface Height (a)[2]	10.5 ± 5.5 m	10.5 ± 5.5 m
Sea Level Rise (y)	25.8 ± 13.2 m	19.4 ± 10.0 m

[1] A "ballpark" estimate of the dip of the Cretaceous shelf based on a range determined from the dip of modern shelves. Reineck and Singh (1972) report a gradient of 1:1333 on the southern North Sea shelf, while Swift and Field (1981) record a gradient of 1:2000 on the Maryland shelf.

[2] An estimation of the Burnstick Member shoreface height based on an average thickness of 5 - 16 m for modern shorefaces (Howard and Reineck, 1981).

Figure 7.4. A table of the measured, assumed and calculated values used to determine the magnitude of sea level rises (y) required to move the shoreface from Garrington to Caroline/Crossfield, and from Caroline/Crossfield to Lochend. The average distance between the belts (x) is measured from Figure 6.1; ϕ and a are estimated from modern environments; and, b and y are calculated from the data. See Figure 7.3 for a schematic description of the parameters.

west are difficult to determine due to the uncertain position of the shorefaces west of the Lochend belt.

(iii) Tectonic Mechanism

In considering the mechanism that caused the sea level fluctuations it is important to determine if the sea level change is a result of global conditions (eustatic) or local conditions (relative). Global sea level curves have been documented by Vail et al. (1977) and further refined by Haq et al. (1987). These curves show a global regression or lowering of sea level during the time of Cardium Formation deposition (Upper Turonian). This lowering of sea level corresponds to Kauffman's (1977) R6, which is a 2 million year regression during the Upper Turonian to Lower Coniacian. This time span covers the entire interval of Cardium Formation deposition.

The resolution of the global sea level curves is by no means detailed enough to isolate the sea level changes within the time span of the Cardium Formation deposition. If the Cardium Formation was deposited in 1 million years (Walker, 1986), and there are seven basin wide erosional surfaces in the Cardium Formation (Plint et al., 1986), then it is possible to divide the Cardium Formation into seven equal time intervals. Each interval represents the time it took to produce the erosional surface and to deposit the sediments on top of the erosional surface. This means that the E4 surface, and the Burnstick Member sediments that rest on top of the E4 surface, took approximately 150,000 years to develop across the Alberta Foreland Basin. Even the refined global sea level curves of Haq et al. (1987) do not show a time frame as short as 150,000 years. Therefore, based on the resolution of the global sea level curves, it can be concluded that the Burnstick Member sea level fluctuations were not eustatic.

The cause of Cretaceous oscillations in sea level in five Canadian basins was studied by Jeletzky (1978). By comparing the sedimentary sequences in five separate basins, Jeletzky (1978) concluded that tectonic processes were primarily responsible for sea level fluctuations in the basins. This argument is based on the poor correlation of the timing of transgressive and regressive events in the five Cretaceous basins. Jeletzky (1978) suggests that differential subsidence, hinge-like movements, tilting, planar rotation and uncoordinated vertical movements could have caused the sea level changes in the basins. It is possible that similar tectonic movements were responsible for the sea level fluctuations during the deposition of the Burnstick Member.

It can be concluded that the sea level fluctuations responsible for "moving" the Burnstick Member shoreface through the basin were caused by local, tectonic processes rather than eustatic processes. The probable mechanism for these fluctuations is tectonic movement within the Cordillera and Alberta Foreland Basin. It will be impossible to isolate the exact tectonic mechanism responsible for the sea level changes until tectonic models, such as those proposed by Beaumont (1981) and Tankard (1986), are able to predict events on a thousand year time scale rather than a million year time scale.

7.4 Burnstick Member Deposition

The purpose of this section will be to interpret the depositional environment of the Burnstick Member sediments. In each of the four fields these sediments rest against the one - sided scour of the incised E4 surface. It seems most likely that the Burnstick Member sediments are shoreface deposits given the interpretation that the underlying E4 surface is a shoreface profile. However, before this conclusion is reached it will be important to compare the sediments of the Burnstick Member to other modern shoreface sequences. In this manner it will be possible to test the hypothesis that the Burnstick Member sediments are shoreface sediments.

(A). Facies Interpretation

The Burnstick Member consists of a distinct coarsening upward vertical facies sequence in all of the four fields. This sequence passes from a speckled gritty mudstone at the base (facies 6) up into a sand supported conglomerate (facies 8) near the top. The average thickness of the Burnstick

Member sequence is approximately 2.7 meters, while the maximum thickness is 6.2 meters in Garrington (10-24-36-6W5).

From the base to the top of the Burnstick Member (BM) sequence the sediments become coarser, have sedimentary structures that pass from wave ripples up into trough cross beds, and are less bioturbated. This seems to indicate that there is an increase in the energy of the depositional environment from the deposition of facies 6 up into the deposition of facies 8. These characteristics of the BM sequence, along with a suite of trace fossils that include Planolites, Teichichnus, Terebellina and Skolithos, all indicate that the BM sequence is a coarsening upward, marine facies sequence.

Observations in modern coastal environments by Clifton et al. (1971) and Howard and Reineck (1981) have led to a better understanding of the sediments in a shoreface environment. Howard and Reineck (1981) compared the beach to offshore sequence in a high energy coast (California) to those in a low energy coast (Georgia), and determined that there was a similar sequence in each environment. This sequence consists of bioturbated sandy silt in the offshore zone, interbedded sand and sandy silt in the transition zone, and cross bedded sandstone in the shoreface zone. As a fundamental rule, this sequence has fewer physical sedimentary structures and more biogenic structures (trace fossils) seaward. These characteristics are very similar to the changes in the BM sequence and indicate that the BM sequence could be a transition - shoreface sequence. Support for this interpretation comes from a comparison of the facies, sedimentary structures, trace fossils, and the underlying geometry of the E4 surface in relation to the characteristics of modern shoreface environments.

Judging by the thickness and facies of the BM sequence, it seems that there are no upper shoreface or foreshore sediments in the BM sequence. Measurements made by Howard and Reineck (1981) suggest that the foreshore - shoreface-transition sequence is between 5 - 16 m thick. Other studies confirm these measurements as the Galveston Island foreshore - shoreface sequence is approximately 10 m thick (McCubbin, 1982). The thickness of modern foreshore-shoreface sequences is considerably greater than the average thickness of the BM sequence (2.7 m). This might suggest that the upper part of the BM sequence has been eroded and is not preserved.

Further support for this hypothesis comes from a comparison of the BM facies sequence to those in a modern upper shoreface - foreshore environment. In a modern shoreface environment well sorted, low angle laminated sands are very common in the beach environment (foreshore), and trough cross bedded sands are very common in the upper shoreface environment (McCubbin, 1982). Both of these facies are not well represented in the BM sequence. Trough cross bedded sandstones are only observed in 20% of the BM cores while low angle laminated sandstones are not observed. From a comparison of the 4 Burnstick Member facies to Reinson's (1984) description of modern shoreface sediments it appears that the BM facies sequence was deposited in a lower to middle shoreface setting. The fate of the upper shoreface and foreshore sediments of the BM sequence will be discussed in Section 7.5.

(B). BM Sequence -- E4 Surface Relationship

Both the E4 surface and the BM facies sequence are interpreted to have developed in a shoreface environment. The E4 surface represents a wave cut shoreface profile while the BM sequence is a coarsening upward shoreface sequence that was deposited on top of the E4 surface.

In most cores there is a concentration of coarse sand, granules and pebbles near the base of the Burnstick Member. These coarse sediments are usually located in the lower one third of facies 6 and define a fairly sharp contact with the Hornbeck Member sediments below (Figure 3.9). It is probable that the coarse sediments at the base of facies 6 are a lag deposit that was winnowed out of the Hornbeck Member sediments during the cutting of the E4 surface. Support for this interpretation comes from two facts; (1) the coarse sediments are always concentrated near the base of the Burnstick Member, near the E4 surface and, (2) ripped up mud clasts are observed in a few of the basal facies 6 sediments. Both of these observations suggest that the coarse grained lag deposit in the basal facies 6 developed during the cutting of the incised E4 surface belts.

(C). Development of the Three BM Belts

Three different Burnstick Member belts are observed in the study area and each belt consists of a coarsening upward Burnstick Member (BM) sequence. All three belts are interpreted to be coarsening upward shoreface deposits that are underlain by a shoreface erosional surface (E4).

In a previous section (7.3Ci), the development of the three incised E4 surface belts was discussed. A similar type of development is proposed for the three Burnstick Member (BM) belts in this section, as it has been shown that the E4 surface belts are genetically related to the BM belts. Both of these belts are interpreted to have developed in a shoreface environment.

It follows from these statements that the BM belts were localized in the Alberta Foreland Basin during relative sea level changes. Sea level changes in the Western Interior Seaway were responsible for moving the shoreface and hence, the locus of deposition from west of the study area to a position at or seaward of Garrington. This produced the cutting of the E4 surface along the Garrington belt and the deposition of a coarsening upward shoreface sequence (BM sequence). Subsequent rises of sea level to the positions of the Caroline - Crossfield and the Lochend belts were responsible for the development of the E4 surface and the deposition of the BM sequences along each of these belts. By having at least three independent positions of the shoreface in the study area it was possible to develop three separate BM sequences. These sequences are interpreted to represent the preserved remains of the shoreface sediments. For a more complete description of the changes in sea level required to move the shoreface across the study area the reader is referred to section 7.3C(1).

7.5 Development of the T4 Surface

The T4 surface is defined by the contact between the Burnstick and the Raven River Members. It is usually a gradational contact, but can be extremely sharp in some of the cores. This contact represents a major change in sedimentation from the predominantly sandy facies of the upper Burnstick Member into the predominantly muddy facies of the lower Raven River Member.

The T4 surface is interpreted to have developed during a rise in sea level and, hence, the lettering T (transgressive) 4. In most cases, this rise in sea level is recorded as a gradual change in sedimentation across the T4 contact.

(A). Evidence for Erosional Shoreface Retreat

In the previous section (7.4A), the hypothesis that the BM sequence represents a lower - middle shoreface sequence was discussed. Based on a comparison of the facies in the BM sequence to those observed in a modern shoreface environment, it appears that this hypothesis is valid. This suggests that the upper shoreface and the beach sediments of the BM sequence were eroded.

By comparing the average thickness of the BM sequence to the average thickness of modern shoreface sequences, it is possible to estimate the thickness of sediments eroded from the BM sequence. Using 10 m as an average shoreface sequence thickness and 2 - 7 m as the range in thickness of the BM sequence, it can be estimated that between 3 - 8 m of the BM sequence was eroded. These sediments would have represented the upper shoreface and beach deposits of the BM sequence. The most logical timing for this erosion would be during the development of the T4 surface.

The T4 surface was developed in each belt during the rise in sea level that moved the shoreface one belt over to the west. This interpretation is based on the vertical facies change across the T4 surface from a sandy shoreface sequence (BM) up into a muddy marine sequence (LRRM), which suggests that the shoreface sediments (BM) are being transgressed. During each rise in sea level, the sediments of the upper shoreface and foreshore environments were reworked as the shoreface "stepped up" over top of the BM belts. This resulted in the erosion of the BM sequence and the re-deposition of the upper shoreface and foreshore sediments as the LRRM sequence and the coarse sediments on top of the E4/T4 surface.

Erosional shoreface retreat is a well documented process that occured extensively during the Holocene transgression (Kraft, 1971; Sanders and Kumar, 1975; Schwartz, 1967; Swift, 1968; Swift, 1975). During erosional shoreface retreat the sea destroys some of the marsh - lagoon and high energy barrier sands (Swift, 1968; Swift, 1975) and re - deposits the coarser sediments as a transgressive veneer during the rise in sea level. The thickness of the sediments eroded during the sea level rise depends on the balance between the rate of sea level rise and the rate of sediment supply to the shoreface (Kraft, 1971; Sanders and Kumar, 1975). If the rate of sea level rise is slow then a large part of the barrier - shoreface superstructure will be eroded. Many examples of partially preserved strandline - barrier island deposits have been identified on the modern shelves based on indirect evidence such as bottom morphology and sedimentary textures (Carter et al., 1986; Field, 1974; McClennen and McMaster, 1971; McMaster and Garrison, 1967; Sanders and Kumar, 1975). Some of these deposits are also underlain by an incised shoreface profile (Section 7.5C). This indicates that erosional shoreface retreat occured extensively during the Holocene transgression.

A similar mechanism is proposed for the development of the T4 surface throughout the study area. During the erosional shoreface retreat the upper part of the BM sequence was planed off, as were the sediments to the west of the "drowned" shoreface. The depth of erosion is estimated at 3 to 8 m which resulted in the planing off of the upper shoreface and beach deposits of the BM sequence, and the non-marine sediments west of the "drowned" shoreface. In this manner, the E4/T4 surface in between the belts would be cut and the thin veneer of sediments would be deposited on this surface as a transgressive lag. It is possible that the LRRM sequence that is deposited on top of the T4 surface represents the reworked remains of the upper shoreface to beach sediments. This will be discussed in more detail in section 7.6A.

(B). Basinwide Development

The T4 surface is observed to cap the three BM belts and is also observed in between the belts forming part of the E4/T4 surface. The T4 surface is interpreted to be an erosional surface that outlines the process of erosional shoreface retreat in the study area. In Section 7.3C(i) a general sequence of events was outlined that related the development of the E4 surface to small sea level changes within the basin. A similar sequence of sea level changes can also explain the development of the T4 surface throughout the study area.

An incised shoreface profile and a coarsening upward shoreface sequence (BM) developed along the Garrington belt after an initial large drop in sea level. This was followed by a rise in sea level that "drowned" the Garrington BM sequence producing the T4 surface on top of the Garrington BM belt. The T4 surface at Garrington is recorded by the transition from the sandy - pebbly facies 7 or facies 8 up into the muddy facies 6P.

As sea level rose, the shoreface moved further west resulting in the cutting of the E4/T4 surface west of Garrington. Wave action eroded the sediments west of Garrington to a depth of 3 - 8 m (Section 7.5A). It is believed that the E4/T4 surface is a continuous surface in between the fields. However, the only evidence for this surface, a thin veneer of coarse sediments, is usually located within 5 km of the western field boundary. Further west of this zone, the E4/T4 surface is difficult to identify in core or on the resistivity well logs. In this position, the E4/T4 surface is most likely represented by a mudstone on mudstone contact.

Eventually sea level stabilized and a new shoreface profile was cut along the Caroline - Crossfield belt. This was followed by the deposition of a coarsening upward shoreface sequence (BM sequence) which was truncated by a further rise in sea level. Thus, the complete cycle repeated itself resulting in the development of the T4 surface on top of the

Caroline - Crossfield BM sequence and the E4/T4 surface west of this belt. A similar cycle accounted for the development of the T4 surface at Lochend and the E4/T4 surface west of Lochend.

Once again, sea level fluctuations are directly responsible for the development of the T4 surface. As the lettering implies, the T4 surface is developed during a transgression resulting in the truncation of the BM sequence in the three belts, the reworking of the BM sediments towards the west and the erosion of the sediments in between the belts.

(C). Relationship of the E4 and T4 Surface

In Chapter 6, three cross sections were constructed that related the Burnstick Member sediments of the Garrington, Caroline/Crossfield and Lochend belts (Figures 6.3, 6.4 and 6.5). These cross sections showed that the E4 surface "stepped up" from the east (Garrington) towards the west (Lochend), outlining a step - like topography. Furthermore, the T4 surface of Garrington is at the same horizon as the E4 surface in Caroline and Crossfield, and the T4 surface at Caroline and Crossfield is at the same horizon as the E4 surface at Lochend. This suggests that the geometry of the T4 surface is directly related to the geometry of the E4 surface.

The relationship between the E4 and the T4 surfaces is interpreted to represent shoreface erosion during a stillstand and subsequent erosion during a transgression. Consider the T4 surface at Garrington and the E4 surface at Caroline (Figure 6.3). As sea level rose, the shoreface moved from a position at Garrington towards a position at Caroline. The upper part of the shoreface at Garrington and the non-marine sediments in between Garrington and Caroline were "planed off" or eroded during the sea level rise. This produced the T4 surface at Garrington and the E4/T4 surface in between Garrington and Caroline. Sea level continued to rise until the shoreface reached a position at or near the Caroline - Crossfield belt. At this position, a new shoreface was cut during a stillstand which produced the E4 surface underneath Caroline and Crossfield. A similar sequence of events reoccured following the deposition of the coarsening upward shoreface sequence at Caroline and Crossfield producing: (1) the T4 surface at Caroline and Crossfield, (2) the E4/T4 surface in between the Caroline/Crossfield and the Lochend belts and, (3) the E4 surface at Lochend.

This discussion is intended to emphasize the connection between the E4 and T4 surfaces in the study area. The development of these two surfaces is interconnected and is not mutually exclusive.

Similar types of stepped shoreface sequences are observed off the NE coast of the United States (McLennen and McMaster, 1971; McMaster and Garrison, 1967; Sanders and Kumar, 1976; Swift, 1975), off the coast of Gibraltar (Flemming, 1965), and on the Great Barrier Reef shelf (Carter et al., 1986). Excellent examples of remnant shorefaces are preserved off Rio Grande do Sul, Brazil, on the Brazilian continental shelf. Two scarps are traceable for over 500 kilometers on the shelf and have been interpreted as relict shoreface profiles (Kowsmann and Costa, 1979). These scarps are 60 m and 110 m below present sea level and developed during stillstands that punctuated the overall Holocene transgression.

The incised shoreface profiles and drowned barrier systems of these "modern" examples all developed during the Holocene transgression. Episodic stillstands, superimposed on an overall transgression, explain the development of the terrace - scarp features. There is a close correlation between the geometry of the "modern" examples with the geometry of the three incised E4 surface belts, which adds further support to the shoreface interpretation.

7.6 Lower Raven River Member Deposition

There are three different facies observed in the lower Raven River Member (LRRM) including facies 6P, facies 1P and facies 1. These three facies form a fining upward sequence that passes from a pebbly mudstone (facies 6P) at the base up into a massive dark mudstone (facies 1) near the top. The base of the LRRM sequence is defined by the contact with the

BM sequence and is marked by the T4 surface. This contact is usually gradational (Figures 3.15 and 3.16).

(A). Facies Interpretation

The purpose of this section is to interpret the depositional environment of the LRRM facies sequence. In the previous sections (7.3B, 7.4A, and 7.5A), it was shown that the E4 surface, the BM facies sequence and the T4 surface all developed in a shoreface environment. A similar type of depositional environment is proposed for the LRRM facies sequence.

The key to interpreting the LRRM sequence is to place it within the context of the E4 surface, BM sequence and T4 surface interpretations. The LRRM facies sequence usually forms a gradational contact with the BM sequence below and is recorded by the change from a predominantly sandy facies up into the muddier facies on top of the T4 surface. This was interpreted in section 7.5A to represent the "drowning" or transgression of the BM sequence.

During each rise in sea level, the upper part of the shoreface and the foreshore sediments were eroded from the BM belts (section 7.4A). The sediments that are preserved on top of the lower - middle shoreface BM sequence consists of well bioturbated, sandy - pebbly mudstones. The coarse grained sediments of these sandy - pebbly mudstones are probably the eroded remnants of the upper shoreface and foreshore sediments of the BM belts. This interpretation is consistent with the Bruun theory of sea level rise that predicts sediments will be eroded from the shoreface during a sea level rise and deposited in the "nearshore bottom" (Schwartz, 1967). This process would explain the concentration of mud clasts, granules and pebbles in the lower part of the LRRM sequence.

As the sea level continued to rise, the shoreface sediments of the BM belts would be in deeper and deeper water. This would make it more difficult to erode the shoreface sediments by fairweather wave processes and would lead to the fining of the LRRM facies. Fewer coarse sediments would be available for deposition along with the finer grained mudstones that are indicative of quiet water deposition.

In some of the cores, facies 6P or facies 1P contain coarse sediment layers that are up to 1 m above the T4 surface. These layers are 2 - 10 cm thick, sharp based and have abundant granules and pebbles. It is possible that the coarse sediment layers are storm deposits that were eroded from the adjacent BM facies sequence. Similar layers have been identified by Bergman (1987) in facies 2 above the E5 surface (Cardium Formation) at Carrot Creek. Bergman (1987) interprets these layers to be storm deposits that were transported towards the east from the Carrot Creek field. A similar type of interpretation is proposed for the coarse sediment layers of the LRRM sequence. This provides further support for the erosion and transport of the shoreface sediments into the basin during the transgression of the BM shoreface belts.

The fining upward LRRM sequence records the "drowning" of the shoreface and provides conclusive evidence for the transgression of the BM shoreface belts. Eventually, the shoreface was "drowned" in very deep water and the massive dark mudstone (facies 1) was deposited. Facies 1 is observed throughout the entire study area on top of the BM and LRRM sequences, and has been informally termed the "black blanket" (Walker, 1983c).

(B). Development of the Three LRRM Belts

Three different LRRM belts are observed in the study area including the Garrington, Caroline - Crossfield and the Lochend belts. The LRRM facies sequence is identical in each one of the three belts suggesting that similar conditions occured during the deposition of this sequence in each belt.

In Sections 7.3C(i), 7.4C and 7.5B, the development of the E4 surface, BM sequence and T4 surface throughout the study area was discussed. Sea level fluctuations within the basin were responsible for developing the three BM belts (Section 7.4C) and are also interpreted to be responsible for developing the three LRRM belts. The LRRM facies sequence was deposited on top of the BM facies sequence as a result of sea level rises over top of the BM shorefaces (Section 7.6A). The sequence, magnitude and cause of these sea level fluctuations was discussed in Section 7.3C. Following the discussions in the previous sections, the LRRM sequence would have developed at Garrington first, followed by the development at Caroline and Crossfield, and finally by the development at Lochend. In this manner, three LRRM sequences would have developed in the study area during the transgression of the Garrington, Caroline - Crossfield and Lochend belts. For a more complete discussion of the sea level fluctuations, the reader is referred to Section 7.3C(i).

7.7 Sediment Supply

It has been established in the previous five sections that the E4 surface, BM sequence, T4 surface and the LRRM sequence all developed in a shoreface environment. Three separate shoreface belts are observed in the study area that consist of a similar sequence of BM and LRRM facies. These shoreface belts include the Garrington, Caroline - Crossfield and the Lochend fields. The purpose of this section will be to determine how the sediments were supplied to the three Burnstick Member (BM) shorefaces.

(A). Sediment Supply Mechanism

Two possibilities exist that could explain the introduction of coarse sediments into the BM shorefaces including a longshore drift system and a fluvial system. Each possibility will be considered separately beginning with the longshore drift system.

In order for the longshore drift system to be the main supplier of sediments to the BM shorefaces it would be necessary to have a coarse grained sediment source located "up - drift" from each BM shoreface. In other words, coarse sediments would be eroded at the shoreface and transported "down - drift" towards the location of the Burnstick Member fields. These sediments would be deposited along the four BM fields as the coarsening upward BM facies sequence.

This interpretation is unlikely for two reasons. First of all, in order to have coarse sediments supplying the longshore drift system at the shoreface it would be necessary to have a coarse deposit right at the shoreface. This implies that there were coarse sandstones and conglomerates in the Hornbeck Member that were being eroded at the shoreface during the cutting of the three incised E4 surface belts. However, there is no evidence of a coarse grained Hornbeck Member deposit within the study area and unless this hypothetical coarse grained deposit were completely eroded, it seems unlikely that the Burnstick Member sediments were recycled from the Hornbeck Member below.

Secondly, there are distinct gaps within each of the three BM belts where there are no Burnstick Member sediments. If the belts were being supplied by the longshore drift system alone, one would expect continuous deposits of sediments "down - drift" from the sediment source. Unless there were multiple points of input into the longshore drift system from the underlying Hornbeck Member, it seems unlikely that the BM sediments were supplied to the three belts by shoreface erosion and longshore drift transport.

This leaves fluvial transport as the other possible sediment supply mechanism to the BM shorefaces. Based on the BM thickness trends shown in the TB-BB isopach maps (Figures 5.1, 5.3, 5.5, and 5.7), it appears that point sources were feeding the BM shorefaces. The thickest deposits of the BM occur in the northern parts of Crossfield (Figure 5.3) and Garrington (Figure 5.5), and are concentrated towards the central area of Caroline (Figure 5.1) and Lochend (Figure 5.7). On either side of these thickness "highs" the BM becomes gradually or rapidly thinner. This is especially true for the BM thickness trend in Garrington, as the thickest BM deposits are localized in a 10 km long zone in the extreme northern part of the field (Figure 5.5). A fluvial sediment supply mechanism seems very likely for the BM sediments in Garrington.

Further evidence for a point souce - fluvial supply mechanism is observed when comparing the location of the thickest BM deposits in Caroline to those at Garrington.

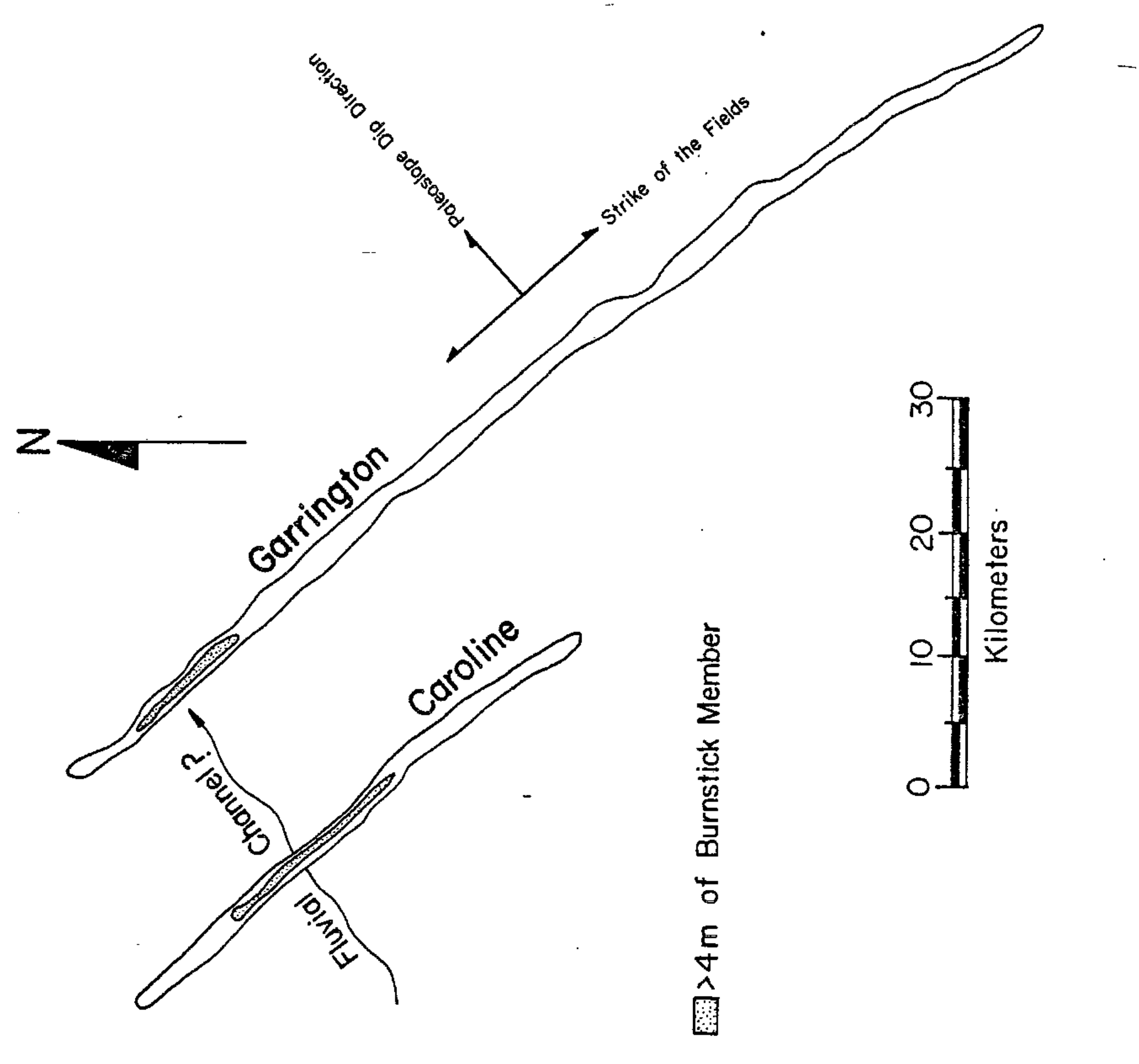
The zones that have greater than 4 m of BM in each field line up perpendicular to the paleoshoreline (Figure 7.5). Individually, the thickness trends of the two fields suggests a point source sediment supply mechanism and together they reinforce this hypothesis. It seems likely that a fluvial system was supplying sediments to these fields.

The indirect evidence for fluvial transport to the BM shorefaces includes the BM thickness trends in each field, the lining up of the thickest BM zones and the concentration of coarse sediments near the base of the Burnstick Member. The latter point implies that sediments of the eroded fluvial channels might be spread across the E4/T4 surface in between the fields and might also be concentrated on the E4 surface in the three incised belts. However, it would be impossible to prove this point as the coarse sediments on the E4 and E4/T4 surfaces could have numerous origins including transgressed shoreface sediments or eroded Hornbeck Member sediments.

(B). Possible Sequence of Events

Based on the limited evidence presented in Section 7.7A, it seems most likely that fluvial processes transported the BM sediments to the incised E4 shorefaces. It is hypothesized that rivers cut across the exposed shelf during the lowering of sea level and deposited sediments at a point source along the incised E4 surface belts. Longshore

Figure 7.5. A comparison of the maximum Burnstick Member thicknesses in Caroline to those in Garrington. The areas of greater than 4 m of Burnstick Member line up parallel to the paleoslope dip direction suggesting a point source or fluvial supply to the two fields.


Paleoslope Dip Direction
Strike of the Fields
N
Garrington
Caroline
Channel ?
Fluvial
>4 m of Burnstick Member
0
10
20
30
Kilometers

currents would have moved the sediments along the shoreface mainly towards the southeast, and also towards the northwest.

Taking the Garrington incised E4 surface belt as an example, a river would have deposited sediments right at the shoreface in the northern part of the field. Longshore currents would have transported the sediments towards the southeast where they were spread out along the incised E4 shoreface. During the subsequent rise in sea level, the fluvial channel would be eroded as the shoreface "stepped up" over top of the Garrington belt. In Section 7.5A, it was estimated that 3 - 8 m of shoreface sediments and non-marine sediments were eroded during the movement of the shoreface from one belt to the next. This depth of erosion would be sufficient to destroy any evidence of a fluvial channel in between the BM belts and might explain why there is no direct evidence of fluvial sedimentation in between the fields.

As sea level rose the shoreface moved from the Garrington to the Caroline - Crossfield belt where it eventually stabilized and cut the incised E4 surface along the Caroline - Crossfield belt. The fluvial system then began to deposit sediments at two separate locations in the study area, one at Caroline and the other at Crossfield. This suggests one of three things; a new channel cut across the exposed shelf, the original channel bifurcated into two channels or the channel deposited the sediments at Caroline first followed by a diversion that brought the channel into the Crossfield area.

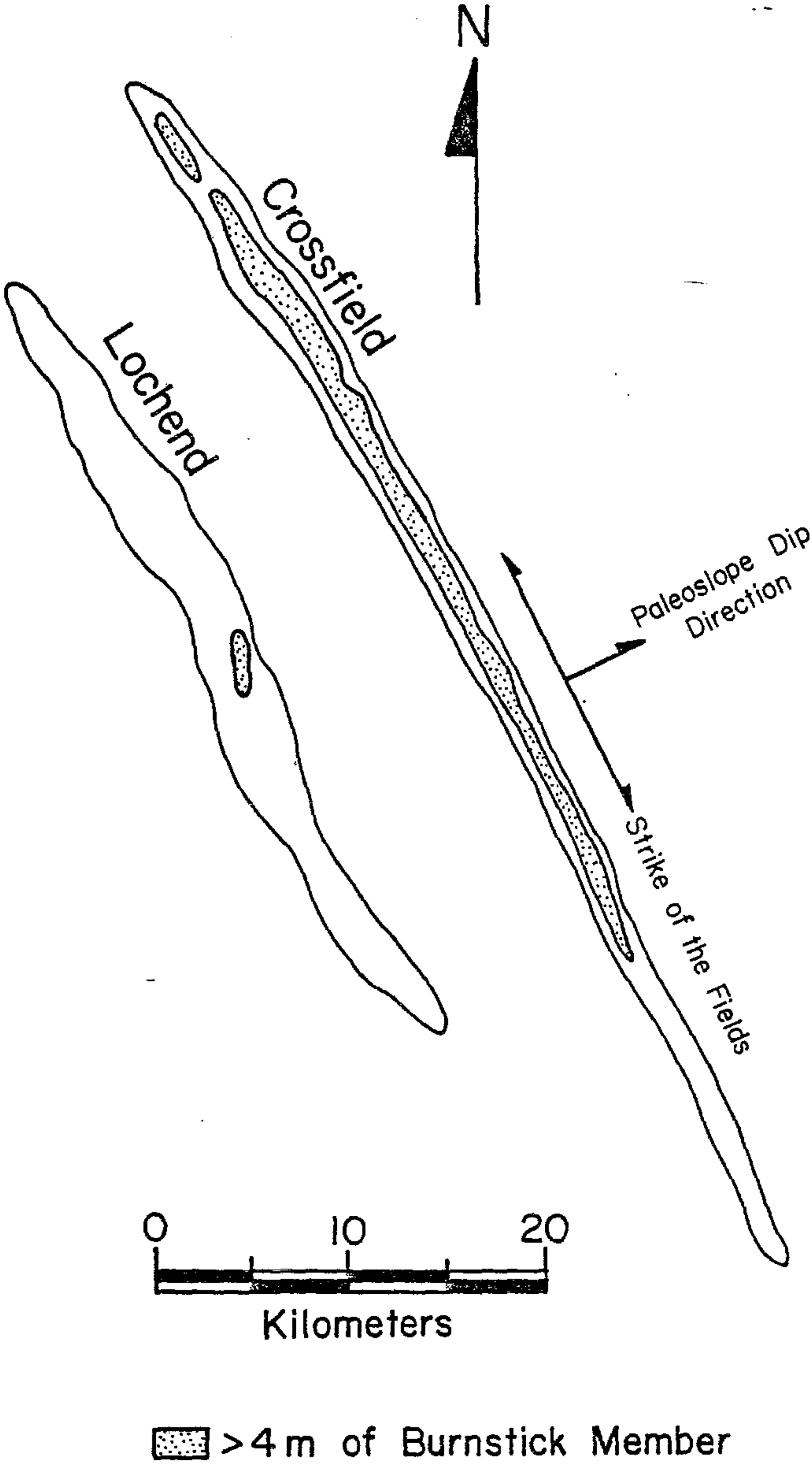
All three situations can explain the two depositional centers on the Caroline - Crossfield belt. A combination of direct fluvial supply to the shoreface and longshore drift transport parallel to the strike of the shoreface would explain the deposition of the Burnstick Member sediments at Caroline and Crossfield.

During the subsequent transgression that "drowned" the Caroline - Crossfield shoreface, the fluvial sediments between the Caroline - Crossfield and Lochend belts were planed off. This was caused by erosional shoreface retreat. Eventually, sea level stabilized at a position at or seaward of the Lochend belt and the incised E4 surface at Lochend was eroded. Sediments were once again trasported to the incised shoreface by a fluvial system.

Based on the observation of only one major depositional field along the Lochend belt it seems that only one channel was feeding this shoreface in the study area. By comparing the location of the maximum thickness of the Burnstick Member in Lochend to that of Crossfield it can be observed that the two trends line up perpendicular to the strike of the fields (Figure 7.6). This suggests that the Crossfield fluvial source is similar to the Lochend fluvial source.

The discussion above is intended to explain the hypothetical sequence of events that would lead to fluvial deposition along each one of the three incised shoreface belts. Two main problems exist with this interpretation and will be discussed below.

Figure 7.6. A comparison of the maximum Burnstick Member thicknesses in Lochend to those in Crossfield. The zones of greater than 4 m of Burnstick Member line up parallel to the paleoslope dip direction. This is indirect evidence for a fluvial supply of sediments to Crossfield and Lochend.


N
Crossfield
Lochend
Paleoslope Dip Direction
Strike of the Fields
0
10
20
Kilometers
>4 m of Burnstick Member

(C). Problems

There are two main problems with suggesting that fluvial channels brought the Burnstick Member sediments to the incised E4 shorefaces. The first problem involves the lack of any direct evidence of channels in between the fields and the second problem involves the expected geometry of the Burnstick Member adjacent to the fluvial input location.

The first problem is by far the most significant as there are no recognized channel geometries or deposits in between the three incised BM belts. The interpretation of fluvial suupply directly into the incised E4 surface belts is based completely on indirect evidence. Based on the interpretation presented in the previous two sections (7.7A and 7.7B), the most likely positions for the fluvial channels can be inferred. However, it is impossible to prove or disprove these ideas based on direct observations of the sediments in between the fields due to the sparse data base in this area. Therefore this interpretation is still in the hypothetical stage.

The second problem with a fluvial interpretation involves the expected geometry of the Burnstick Member deposits at the inferred point of fluvial input into each field. If a river were depositing sediments into a shoreface environment it would be expected that the shoreline would prograde or bulge out close to the input location. In this manner, a small delta would have developed. However, no irregularities of the shoreline are observed near the inferred points of fluvial input into the fields. This might be explained by a greater amount of energy in the receiving basin (wave energy) than in the fluvial system which would tend to "paste" the sediments against the incised shoreface. Nevertheless, this lack of a protruded shoreline seems to weaken the fluvial supply interpretation.

At best, the fluvial supply of sediments to the incised E4 surfaces is proven by indirect evidence (Section 7.7A). When this interpretation is analyzed in context with the interpretations of the E4 surface, BM sequence, T4 surface and the LRRM sequence, the idea of fluvial transport of sediments across the exposed shelf becomes plausible. The destruction of the upper part of the BM shoreface and the development of the E4/T4 surface in between the fields provides evidence for erosion of up to 3 - 8 m of sediments during the transgressions (Section 7.5A). It is likely that the proposed fluvial channels were eroded during these transgressions and are, therefore, not preserved in between the fields.

7.8 Summary : Sea Level Fluctuations are the Key.

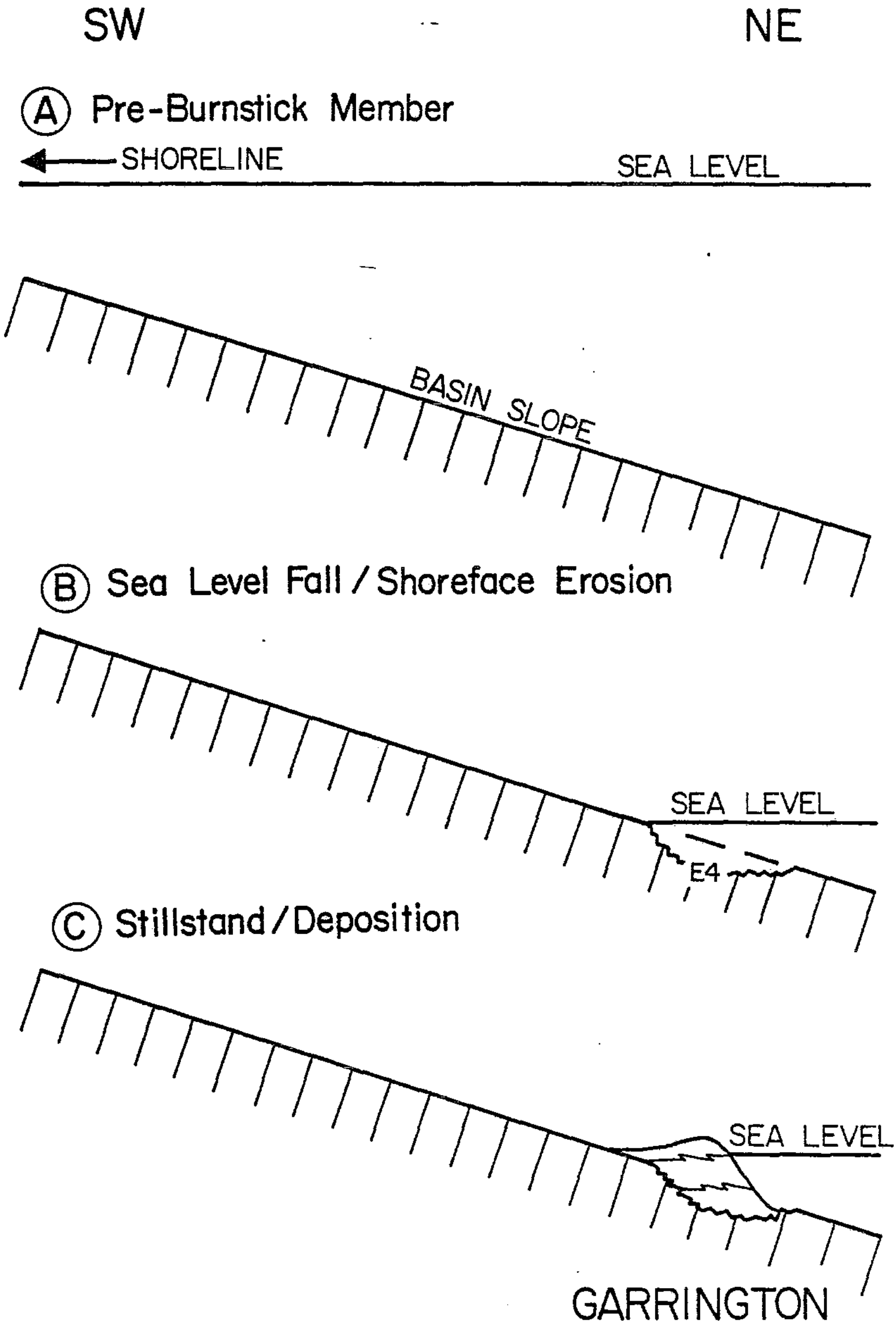
The purpose of this section is to relate the interpretations of the previous six sections into one all encompassing interpretation. This is presented schematically in Figure 7.7.

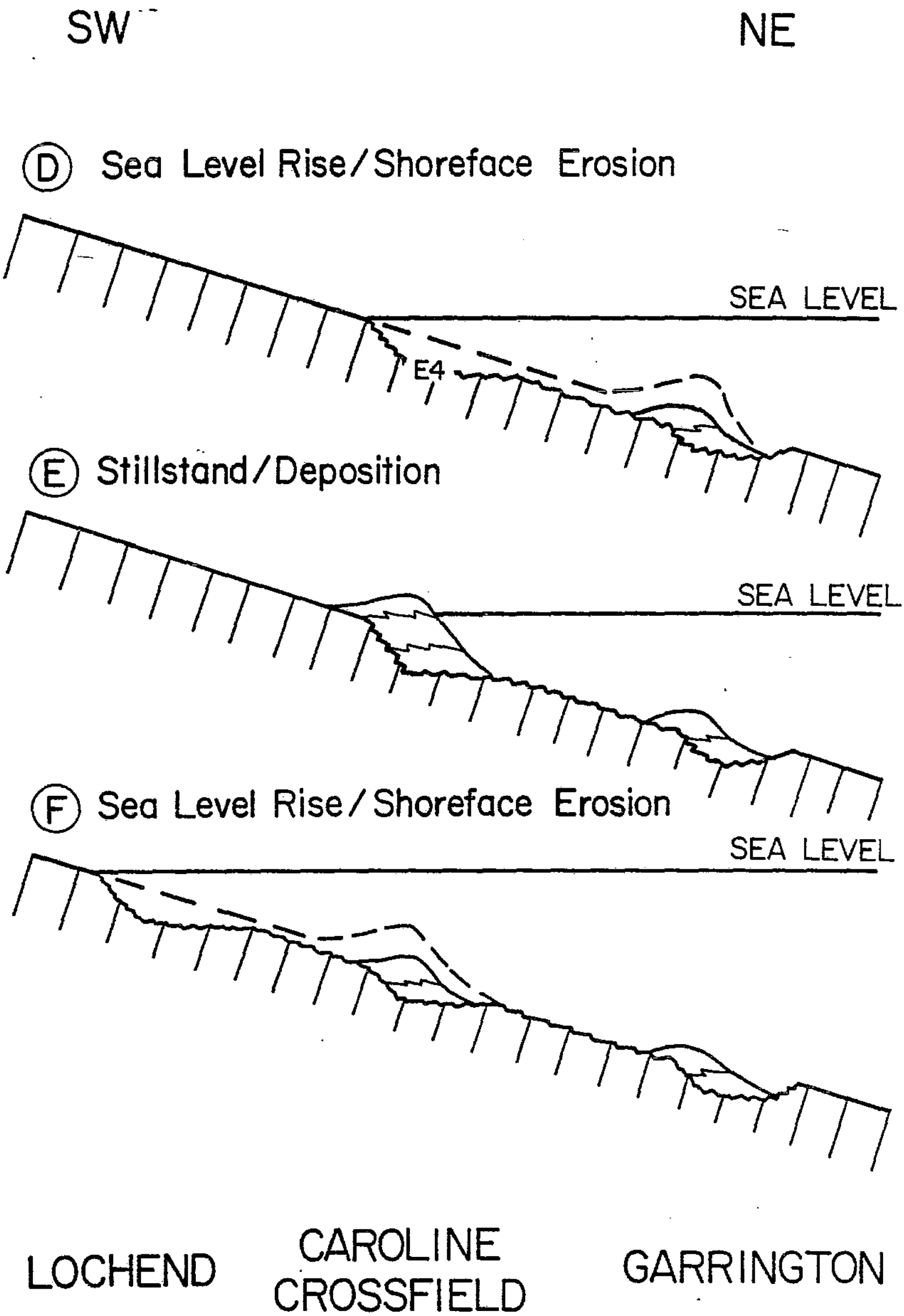
Figure 7.7 consists of nine separate cartoons (A to I) that show the development of the three Burnstick Member belts; Garrington, Caroline - Crossfield and Lochend. These cartoons are cross sections that are constructed perpendicular to the strike of the belts. No scale, vertical or horizontal, is implied in Figure 7.7.

Sea level fluctuations are the key mechanism responsible for controlling the position and development of the three Burnstick Member belts. After the initial lowering of sea level that moved the shoreface from a position west of the study area to a position equivalent to the Garrington belt, the incised E4 surface along the Garrington belt was cut (Figures 7.7A and 7.7B). A coarsening upward, shoreface sequence was deposited on top of the E4 surface at Garrington during a relative stillstand (Figure 7.7C). This sequence was then eroded during a transgression resulting in the planing off of the upper shoreface and foreshore sediments along the Garrington belt. The non - marine sediments in between the Garrington and the Caroline - Crossfield belts were also "planed off" during the transgression (Figure 7.7D). Eventually, sea level stabilized and a new shoreface was cut along the Caroline - Crossfield belt (Figure 7.7D). The interpreted paleogeography at the time of the deposition of the Caroline and Crossfield BM sequence is shown in Figure 7.8.

A similar sequence of events resulted in the development of the BM sediments along the Caroline - Crossfield and

Figure 7.7. The next three pages show the interpreted sequence of events leading to the deposition of the three BM belts in Garrington, Caroline - Crossfield, and Lochend (A to I). Sea level fluctuations are the key mechanisms that control the location of deposition for the three BM belts. All of the diagrams are cross sections that are constructed perpendicular to strike of the three belts. No vertical or horizontal scale is implied.


SW
NE
(A) Pre-Burnstick Member
SHORELINE
SEA LEVEL
BASIN SLOPE
(B) Sea Level Fall / Shoreface Erosion
SEA LEVEL
E4
(C) Stillstand / Deposition
SEA LEVEL
GARRINGTON


SW
NE
D Sea Level Rise/Shoreface Erosion
SEA LEVEL
E4
E Stillstand/Deposition
SEA LEVEL
F Sea Level Rise/Shoreface Erosion
SEA LEVEL
LOCHEND
CAROLINE
CROSSFIELD
GARRINGTON

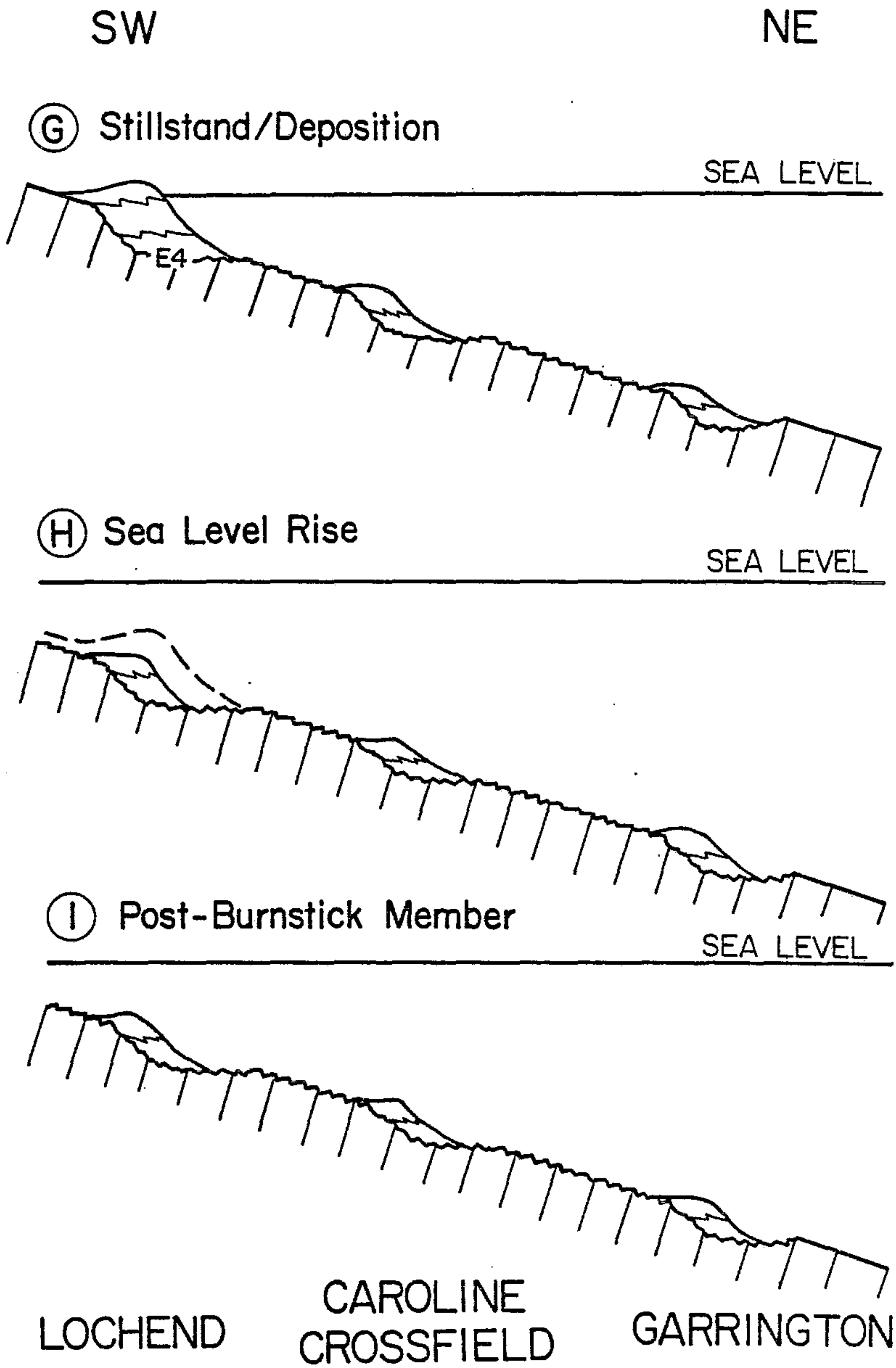
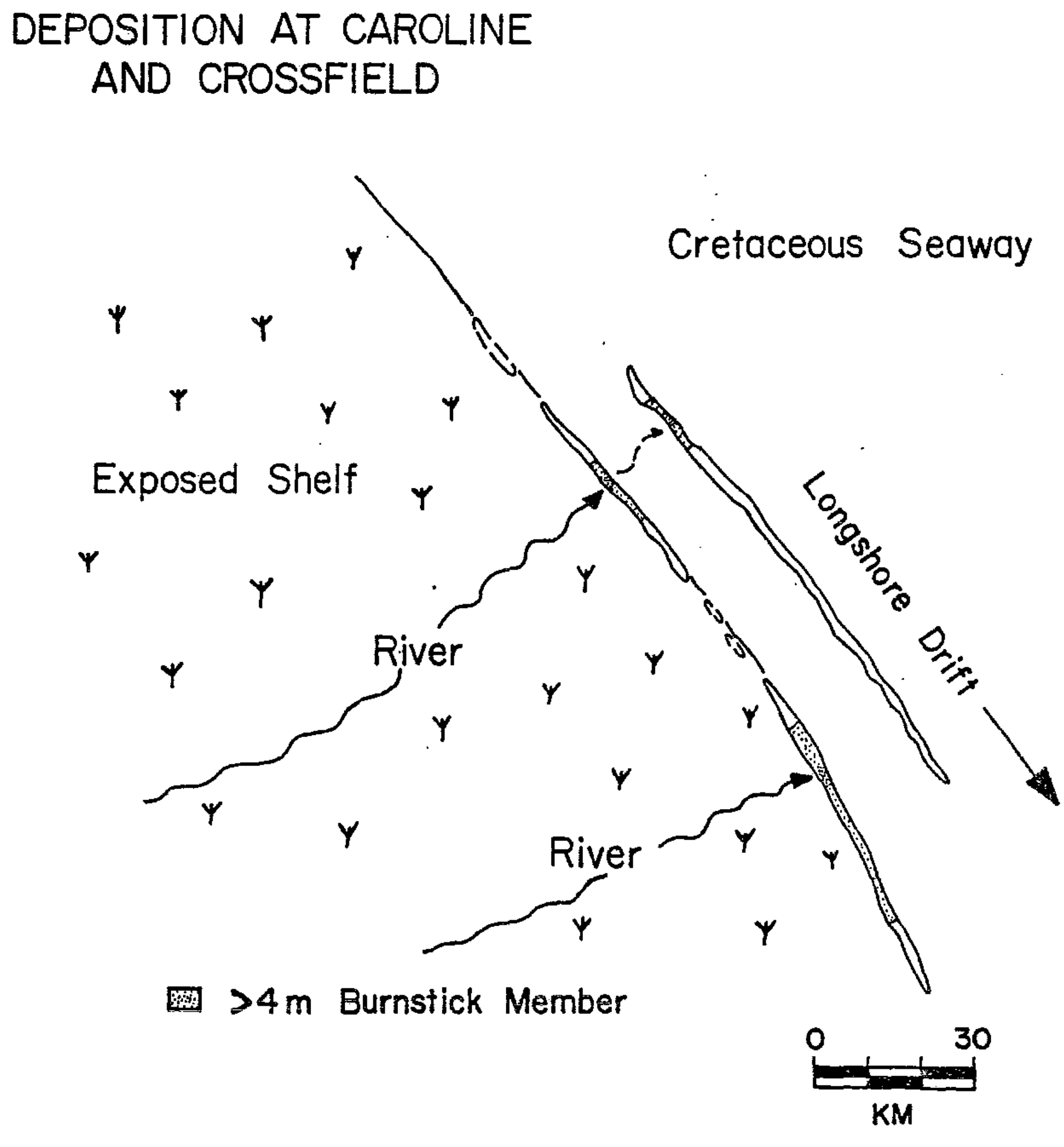

SW
NE
G Stillstand/Deposition
SEA LEVEL
E4
H Sea Level Rise
SEA LEVEL
I Post-Burnstick Member
SEA LEVEL
LOCHEND
CAROLINE
CROSSFIELD
GARRINGTON

Figure 7.8. A plan view of the interpreted paleogeography during the deposition of the Burnstick Member sediments at Caroline and Crossfield. Note the location of the exposed shelf and the Cretaceous Western Interior Seaway in relation to the shoreface sediments in the Caroline - Crossfield belt. Rivers are interpreted to supply the sediments directly to the two fields.


DEPOSITION AT CAROLINE
AND CROSSFIELD
Cretaceous Seaway
Exposed Shelf
Longshore Drift
River
River
>4 m Burnstick Member
0
30
KM

Lochend belts. This is shown schematically in Figures 7.7E to 7.7I. The cycle of stillstand - sea level rise - still-stand -sea level rise led to the development of the E4 surface, BM sequence, T4 surface, LRRM sequence and E4/T4 surface in the Caroline - Crossfield and Lochend areas. The final cartoon of the sequence, Figure 7.7I, shows the pre-served remnants of the three different BM shorefaces drowned under tens of meters of water.

The superimposition of stillstands onto an overall transgression lead to the development of the three BM belts. These three BM belts are completely surrounded by marine mudstones due to shoreface erosion and deposition in a previously shelf environment. When observed in context with the surrounding marine mudstones, it would be easy to inter-pret the BM sediments as offshore deposits. However, given that the E4 surface (Section 7.3), BM sequence (Section 7.4), T4 surface (Section 7.5), and LRRM sequence (Section 7.6), are interpreted to have developed in a shoreface environment, an offshore developement of these features seems unlikely.

The original geological problem of this thesis was to determine how the BM sediments were transported and focussed into the apparantly "offshore" marine environment. One half of this problem has been conclusively solved, as the BM belts are interpreted to have been focussed in a shoreface environ-ment as a result of relative sea level changes in the basin. The other half of the problem, transporting the BM sediments into the long and narrow belts, has been discussed but not conclusively solved due to the lack of direct evidence of fluvial deposits in the study area (Section 7.7C). However, the indirect evidence seems to suggest a fluvial supply to the BM belts which adds further support to the shoreface interpretation.

CHAPTER 8: Conclusions

(1). The base of the Burnstick Member is defined by the erosion surface E4. The E4 surface erodes 2 - 6 m of shelf sediments (Hornbeck Member facies), dips 0.03 - 0.11° north-eastward and outlines a one-sided scour or bevel underneath the four fields. This surface is interpreted to have developed in a shoreface environment.

(2). The Burnstick Member sediments are up to 7 m thick and rest within the one-sided scours of the E4 surface. These sediments are interpreted to be lower - middle shoreface sediments that were localized on the Cretaceous shelf during a lowering of sea level. The upper shoreface and foreshore sediments of this sequence were probably eroded during subsequent rises in sea level.

(3). The E4 surface underneath the fields and the E4/T4 surface in between the fields combine to form a step-like topography across the study area. This topography developed during an overall transgression which was punctuated by three periods of stillstands. The E4 surface developed along the Garrington, Caroline/Crossfield and Lochend fields during the three stillstands, while the E4/T4 surface between the fields developed as a result of erosional shoreface retreat during sea level rises.

(4). There are three positions of the Burnstick Member shoreface in the study area, which coincide with the Garrington, Caroline/Crossfield, and Lochend fields. An initial large drop in sea level moved the shoreface from west of the study area to Garrington. Three smaller rises in sea level moved the shoreface from Garrington to Caroline/Crossfield, from Caroline/Crossfield to Lochend, and from Lochend to west of the study area. A sea level rise of 25.8 ± 13.2 m moved the shoreface from Garrington to Caroline/Crossfield, while a sea level rise of 19.4 ± 10.0 m moved the shoreface from Caroline/Crossfield to Lochend.

(5). The sea level fluctuations were probably caused by a tectonic mechanism.

(6). Fluvial channels probably supplied sediments directly to the E4 shorefaces by cutting across the exposed shelf during the lowering of sea level. These sediments were then reworked along the shoreface and transported mainly to the southeast by longshore currents.

(7). The possibility exists that there are other Burnstick Member fields along the strike of the present fields or along an adjacent, parallel "shoreface" belt. This would suggest other sources of input to the shorefaces and additional, stable positions of the shoreface in the basin. It is also possible that there are preserved fluvial channels between the fields.

REFERENCES

BARRON, E.J., and WASHINGTON, W.M., 1982. Cretaceous climate: a comparison of atmospheric simulations with the geologic record. Paleogeography, Paleoclimatology, Paleoecology, V. 40, p. 103-133.

BARTLETT, J.J., 1987. An analysis of sequence boundaries of the event stratigraphy of the Cardium Formation, Alberta. M.Sc. Thesis, McMaster University, 185 p.

BEACH, F.K., 1955. Cardium a turbidity current deposit. Journal of the Alberta Society of Petroleum Geologists, v. 3, p. 123-125.

BEAUMONT, C., 1981. Foreland basins. Geophysical Journal of the Royal Astronomical Society, v. 65, p. 291-329.

BERGMAN, K.M., 1987. Erosion surfaces and gravel shorefaces deposits: the influence of tectonics on the sedimentology of the Carrot Creek Member, Cardium Formation (Turonian, Upper Cretaceous), Alberta, Canada. Ph.D. Thesis, McMaster University, 404 p.

BERGMAN, K.M., and WALKER, R.G.,, 1987. The importance of sea-level fluctuations in the formation of linear conglomeratic bodies; Carrot Creek Member of the Cardium Formation, Cretaceous Western Interior Seaway, Alberta, Canada. Journal of Sedimentary Petrology, v. 57, p. 651-665.

BERVEN, R.J., 1966. Cardium sandstone bodies, Crossfield -

Garrington area, Alberta. Bulletin of Canadian Petroleum Geology, v. 14, p. 208-240.

CARTER, R.M., CARTER, L., and JOHNSON, D.P., 1986. Submergent shorelines in the SW Pacific: evidence for an episodic post - glacial transgression. Sedimentology, v. 33, p. 629-649.

CLIFTON, H.E., HUNTER, R.E., and PHILLIPS, R.L., 1971. Depositional structures and processes in the non-barred high-energy nearshore. Journal of Sedimentary Petrology, v. 41, p. 651-670.

COUILLARD, R., and IRVING, E., 1975. Paleolatitude and reversals: evidence from the Cretaceous period. In: W.G.E. Caldwell (ed.), The Cretaceous System in the Western Interior of North America, GAC Spec. Publ. 13, p. 21-30.

DAMUTH, J.E., and FLOOD, R.D., 1985. Amazon Fan, Atlantic Ocean. In: Bouma, A.H., Normark, W.R., and Barnes, N.E. (eds.), Submarine Fans and Related Turbidite Systems, Springer-Verlag, New York, p. 97-106.

DE WIEL, J.E.F., 1956. Viking and Cardium not turbidity current deposits. Journal of the Alberta Society of Petroleum Geologists, v. 4, p. 173-175.

DUKE, W.L., 1985. Sedimentology of the Upper Cretaceous (Turonian) Cardium Formation in outcrop in southern Alberta. Ph.D. Thesis, McMaster University.

FIELD, M.E., 1974. Buried strandline deposits on the central Florida inner continental shelf. Geological Society of America Bulletin, v. 85, p. 57-60.

FLEMMING, N.C., 1965. Form and relation to present sea level of Pleistocene marine erosion features. Journal of Geology, v. 73, p. 799-811.

HAQ, B.V., HARDENBOL, J., and VAIL, P.R., 1987. Chronology of fluctuating sea levels since the Triassic. Science, v. 235, p. 1156-1167.

HILL, G.W., and HUNTER, R.E., 1976. Interaction of biological and geological processes in the beach and nearshore environments, northern Padre Island, Texas. In: Davis, R.A., Jr., and Ethington, R.L., (eds.), Beach and Nearshore Sedimentation, SEPM Spec. Pub. 24, p. 169-187.

HOWARD, J.D., and REINECK, H.E., 1981. Depositional facies of high energy beach-to-offshore sequence: comparison with low energy sequence. AAPG Bulletin, v. 65, p. 807-830.

JELETZKY, J.A., 1978. Causes of Cretaceous oscillations of sea level in Western and Arctic Canada and some general geotectonic implications. Geological Survey of Canada, Paper 77-18, 38 p.

JONES, R.M.P., 1980. Basinal isostatic adjustment faults and their petroleum significance. Bulletin of Canadian Petroleum Geology, v. 28, p. 211-251.

KAUFFMAN, E.G., 1977. Geological and biological overview:

Western Interior Cretaceous Basin. Mountain Geologist, v. 14, p. 75-99.

KOWSMANN, R.O., and COSTA, M.P.A., 1979. Evidence of Late Quaternary sea level stillstands on the Upper Brazilian continental margin: a synthesis. In: K. Suguio, T.R. Fairchild, L. Martin and J.M. Flexor (eds.), Proceedings of the "1978 International Symposium on Coastal Evolution in the Quaternary", Sao Paulo, Brasil, p. 170-192.

KRAUSE, F.F., and NELSON, D.A., 1984. Storm event sedimentation: lithofacies association in the Cardium Formation, Pembina area, west-central Alberta, Canada. In: D.F. Stott and D.J. Glass (eds.), The Mesozoic of Middle North America. Canadian Society of Petroleum Geologists, Memoir 9, p. 485-511.

KUMAR, N., and SANDERS, J.E., 1976. Characteristics of shoreface storm deposits: modern and ancient examples. Journal of Sedimentary Petrology, v. 46, p. 145-162.

LEGGITT, S.M., 1987. Facies geometry and erosion surfaces in the Cardium Formation, Pembina field, Alberta, Canada. M.Sc. Thesis, McMaster University, 183 p.

MACDONALD, W.D., 1957. The Upper Cretaceous Cardium Formation between Athabasca River and the Peace River. Journal of the Alberta Society of Petroleum Geology, v. 5, p. 82-88.

MCCLENNEN, C.E., and MCMASTER, R.L., 1971. Probable Holocene transgressive effects on the geomorphic features of the continental shelf off New Jersey, United States. Maratime Sediments, v. 7, p. 69-72.

MCCUBBIN, D.G., 1982. Barrier - island and strand - plain facies. In: Scholle, P.A., and Spearing, D.R., (eds.), Sandstone Depositional Environments, AAPG, Memoir 31, p. 247-280.

MCLEAN, D.J., 1987. Geometry of facies packages and E5 erosion surface in the Cardium Formation. M.Sc. Thesis, McMaster University, 144 p.

MCMASTER, R.L., and GARRISON, L.E., 1967. A submerged Holocene shoreline near Block Island, Rhode Island. Journal of Geology, v. 75, p. 335-340.

MICHAELIS, E.W., 1957. Cardium sedimentation in the Pembina River area. Journal of the Alberta Society of Petroleum Geology, v. 5, p. 73-77.

MICHAELIS, E.W., and DIXON, G., 1969. Interpretation of depositional processes from sedimentary structures in the Cardium sand. Bulletin of Canadian Petroleum Geology, v. 17, p. 410-443.

NIELSEN, A.R., 1957. Cardium stratigraphy of the Pembina field. Journal of the Alberta Society of Petroleum Geologists, v. 5, p. 64-72.

NIELSEN, A.R., and PORTER, J.W., 1984. Pembina oil field--in retrospect. In: D.F. Stott and D.J. Glass (eds.), The Mesozoic of Middle North America. Canadian Society of Petroleum Geologists, Memoir 9, p. 1-13.

PALMER, A.R., 1983. The decade of North American geology. 1983 geological time scale. Geology, v. 11, p. 503-504.

PARRISH, J.T., GAYNOR, G.C., and SWIFT, D.J.P., 1984. Circulation in the Createceous Western Interior Seaway of North America, a review. In: D.F. Stott and D.J. Glass (eds.), The Mesozoic of Middle North America, CSPG Memoir 9, p. 221-231.

PLINT, A.G., and WALKER, R.G., 1986. Cardium Formation 8. Facies and environments of the Cardium shoreline and coastal plain in the Kakwa Field and adjacent areas, Northwestern Alberta. Bulletin of Canadian Petroleum Geology, v. 34, p.

PLINT, A.G., WALKER, R.G., and BERGMAN, K.M., 1986. Cardium Formation 6: Stratigraphic framework of the Cardium in subsurface. Bulletin of Canadian Petroleum Geology, v. 34 (2), p. 213-225.

RAMPINO, M.R., and SANDERS, J.E., 1980. Holocene transgression in south-central Long Island, New York. Journal of Sedimentary Petrology, v. 50, p. 1063-1080.

REINECK, H.E., and SINGH, I.B., 1972. Genesis of laminated sand and graded rhythmites in storm-sand layers of shelf mud. Sedimentology, v. 18, p. 123-128.

REINSON, G.E., 1984. Barrier-island and associated strand-plain systems. In: Walker, R.G., (ed.), Facies Models, Geoscience Canada Reprint Series 1 (second edition), p. 119-140.

RICE, D.D., and GAUTIER, D.L., 1983. Patterns of Sedimentation, Diagenesis, and Hydrocarbon Accumulation in Cretaceous Rocks of the Rocky Mountains. SEPM Short Course 11, 317 p.

ROESSINGH, H.K., 1957. The Cardium Formation in the Alberta Plains between Athabasca River and Bow River. Journal of the Alberta Society of Petroleum Geology, v. 5, p. 78-81.

SANDERS, J.E., and KUMAR, N., 1975. Evidence of shoreface retreat and in place "drowning" during Holocene submergence of barriers, shelf off Fire Island, New York. Geological Society of America Bulletin, v. 86, p. 65-76.

SCHWARTZ, M.L., 1967. The Bruun theory of sea level rise as a cause of shore erosion. Journal of Geology, v. 75, p. 76-92.

STOTT, D.F., 1963. The Cretaceous Alberta Group and equivalent rocks, Rocky Mountain Foothills, Alberta. Geological Survey of Canada, Memoir 317, 306 p.

SWAGOR, N.S., OLIVER, T.A., and JOHNSON, B.A., 1976. Carrot Creek Field, Central Alberta. In: M.M. Lerand (ed.), The Sedimentology of Selected Clastic Oil and Gas Reservoirs in Alberta. Canadian Society of Petroleum Geologists, p. 78-95.

SWIFT, D.J.P., 1968. Coastal erosion and transgressive stratigraphy. Journal of Geology, v. 76, p. 444-456.

SWIFT, D.J.P., 1975. Barrier island genesis: evidence from the Middle Atlantic Shelf of North America. Sedimentary Geology, v. 14, p. 1-43.

SWIFT, D.J.P., and FIELD, M.E., 1981. Evolution of a classic sand ridge field: Maryland sector, North American inner shelf. Sedimentology, v. 28, p. 461-482.

SWIFT, D.J.P., and NIEDORODA, A.W., 1985. Fluid and sediment dynamics on continental shelves. In: R.W. Tillman et al. (eds.), Shelf Sands and Sandstone Reservoirs. SEPM Short Course No. 13, p. 47-134.

SWIFT, D.J.P., and RICE, D.D., 1984. Sand bodies on muddy shelves: a model for sedimentation in the Western Interior Cretaceous Seaway, North America. In: R.W. Tillman and C.T. Siemers (eds.), Siliciclastic Shelf Sediments, SEPM Spec. Publ. 34, p. 43-62.

TANKARD, A.J., 1986. On the depositional response to thrusting and lithospheric flexure: examples from the Appalachian and Rocky Mountain basins. In: P.A. Allen and P. Homewood (eds.), Foreland Basins, International Association of Sedimentologists, Spec. Publ. Number 8, p. 369-392.

VAIL, P.R., MITCHUM, R.M., and THOMPSON, S., 1977. Seismic stratigraphy and global changes of sea level, part four: global cycles of relative changes of sea level. AAPG, Memoir 26, p. 83-98.

WALKER, R.G., 1983a. Cardium Formation 1. "Cardium a turbidity current deposit" (Beach, 1955): a brief history of ideas. Bulletin of Canadian Petroleum Geology, v. 31, p. 205-212.

WALKER, R.G., 1983b. Cardium Formation 2. Sand body geometry in the Garrington - Caroline - Ricinus area, Alberta -- the "ragged blanket" model. Bulletin of Canadian Petroleum Geology, v. 31, p. 14-26.

WALKER, R.G., 1983c. Cardium Formation 3. Sedimentology and stratigraphy in the Garrington - Caroline area, Alberta. Bulletin of Canadian Petroleum Geology, v. 31, p. 213-230.

WALKER, R.G., 1985. Cardium Formation at Ricinus Field, Alberta: a channel cut and filled by turbidity currents in the Cretaceous Western Interior Seaway. American Association of Petroleum Geologists Bulletin, v. 69, p. 1963-1981.

WALKER, R.G., 1986. Cardium Formation 7. Progress report compiling data from outcrop and subsurface in southern Alberta. McMaster University, Tech. Memo 86-3, 97 p.

WILLIAMS, G.D., and STELCK, C.R., 1975. Speculations on the Cretaceous paleogeography of North America. In: W.G.E. Caldwell (ed.), The Cretaceous System in the Western Interior of North America, GAC Spec. Paper 13, p. 1-20.

WRIGHT, M.E., and WALKER, R.G., 1981. Cardium Formation (Upper Cretaceous) at Seebe, Alberta -- storm-transported sandstones and conglomerates in shallow marine depositional environments below fairweather wave base. Canadian Journal of Earth Sciences, v. 18, p. 795-809.

APPENDIX

A listing of all the cores (location and depth) that were examined for this thesis. The cores are listed by their location in either Caroline, Crossfield, Garrington, Lochend or the off-field areas. Core sections and descriptions are available upon request from the author.

Caroline

10-30-33-5W5	2345.6-2366.0
11-36-33-6W5	2400.2-2418.8
04-01-34-6W5	2414.6-2432.6
10-02-34-6W5	2413.9-2432.2
10-10-34-6W5	2436.0-2446.0
04-11-34-6W5	2437.0-2454.0
10-16-34-6W5	2456.6-2461.7
06-21-34-6W5	2467.2-2474.6
12-21-34-6W5	2454.0-2465.4
05-28-34-6W5	2446.0-2452.6
07-29-34-6W5	2461.0-2465.0
11-29-34-6W5	2456.6-2473.6
07-31-34-6W5	2472.7-2481.9
11-31-34-6W5	2484.6-2496.5
07-32-34-6W5	2435.0-2455.0
04-05-35-6W5	2461.6-2468.6
12-06-35-6W5	2486.0-2504.2
03-07-35-6W5	2481.0-2499.0
10-01-35-7W5	2514.0-2522.6
16-11-35-7W5	2506.0-2524.4
08-12-35-7W5	2493.0-2503.0
04-13-35-7W5	2514.0-2532.0
05-22-35-7W5	2509.9-2525.4
16-31-35-7W5	2570.0-2588.0
10-32-35-7W5	2558.0-2564.0
02-14-36-8W5	2533.1-2550.7
10-22-36-8W5	2633.0-2645.8
03-23-36-8W5	2592.8-2610.8
12-33-36-8W5	2594.3-2605.0
04-08-37-8W5	2612.3-2630.6

Crossfield

14-23-25-1W5	1752.0-1760.2
08-26-25-1W5	1758.7-1770.9
10-03-26-1W5	1823.9-1833.3
16-03-26-1W5	1808.9-1824.2
16-16-26-1W5	1841.9-1850.1
06-05-27-1W5	1948.6-1965.0
06-07-27-1W5	2004.4-2019.6
16-07-27-1W5	1958.2-1973.5
06-24-27-2W5	2033.0-2045.2
08-26-27-2W5	2051.3-2061.4
06-35-27-2W5	2041.5-2059.7
16-35-27-2W5	2039.9-2055.8
10-03-28-2W5	2051.0-2066.5
06-21-28-2W5	2063.8-2079.0
06-22-28-2W5	2023.6-2040.0
08-28-28-2W5	2045.2-2057.7
08-29-28-2W5	2070.4-2075.0
16-29-28-2W5	2064.9-2069.5

Crossfield (con't)

16-32-28-2W5	2060.1-2068.9 m
06-33-28-2W5	2058.8-2069.8
06-05-29-2W5	2044.2-2051.5
10-05-29-2W5	2058.9-2071.1
16-12-29-3W5	2017.7-2020.7
16-23-29-3W5	2040.5-2049.7
08-24-29-3W5	2018.3-2025.9
06-25-29-3W5	2011.7-2022.0
14-25-29-3W5	2019.3-2027.8
16-26-29-3W5	2017.8-2026.6
06-35-29-3W5	2029.9-2042.2
16-35-29-3W5	2003.1-2014.7
14-02-30-3W5	2016.3-2025.7
06-03-30-3W5	2055.5-2066.2
16-08-30-3W5	2104.6-2119.2
06-09-30-3W5	2097.0-2107.1
16-09-30-3W5	2075.0-2087.8
06-10-30-3W5	2057.6-2076.5
08-10-30-3W5	2025.9-2042.7
06-15-30-3W5	2038.2-2045.2
06-16-30-3W5	2084.7-2091.1
16-16-30-3W5	2036.0-2045.1
16-19-30-3W5	2132.9-2136.6
06-20-30-3W5	2109.1-2118.3
14-20-30-3W5	2118.3-2127.8
16-20-30-3W5	2097.0-2103.7
06-21-30-3W5	2082.3-2086.3
14-21-30-3W5	2074.8-2085.1
16-31-30-3W5	2115.9-2122.0
06-32-30-3W5	2121.1-2127.2
14-06-31-3W5	2133.6-2145.7
14-01-31-4W5	2155.2-2162.8
06-13-31-4W5	2136.6-2151.9
08-14-31-4W5	2162.5-2173.1

Garrington

08-11-30-1W5	1731.6-1741.0
16-15-30-1W5	1772.0-1783.0
06-04-31-1W5	1795.3-1812.6
08-05-31-1W5	1803.0-1813.0
16-05-31-1W5	1808.0-1815.2
06-19-31-1W5	1799.0-1817.0
10-24-31-2W5	1821.0-1831.1
06-25-31-2W5	1818.5-1830.3
10-25-31-2W5	1798.3-1813.6
04-36-31-2W5	1807.4-1815.0
04-02-32-2W5	1836.7-1848.5
10-03-32-2W5	1847.3-1854.6
10-09-32-2W5	1851.9-1862.5
04-11-32-2W5	1831.8-1846.4

Garrington (con't)

04-29-32-2W5	1907.0-1912.5 m
10-36-32-3W5	1929.3-1935.4
06-01-33-3W5	1927.2-1936.9
16-10-33-3W5	1938.4-1945.4
06-11-33-3W5	1928.1-1931.1
06-14-33-3W5	1954.9-1962.2
06-15-33-3W5	1949.1-1956.1
16-15-33-3W5	1954.6-1960.1
16-16-33-3W5	1959.8-1964.0
06-21-33-3W5	1933.9-1949.1
06-22-33-3W5	1984.5-1986.9
06-28-33-3W5	1939.0-1945.1
14-28-33-3W5	1961.9-1975.0
16-28-33-3W5	1928.7-1936.6
16-29-33-3W5	1989.6-1994.5
06-32-33-3W5	2023.8-2027.4
16-32-33-3W5	2004.0-2010.1
06-33-33-3W5	1965.9-1975.0
06-06-34-3W5	2020.7-2030.2
16-06-34-3W5	1990.2-1994.5
06-07-34-3W5	2007.6-2011.9
16-01-34-4W5	2024.1-2032.0
06-12-34-4W5	2023.8-2039.0
16-12-34-4W5	2005.5-2017.1
02-13-34-4W5	2014.6-2018.3
11-13-34-4W5	2010.7-2016.8
01-14-34-4W5	2011.6-2017.7
09-14-34-4W5	1987.0-1994.0
11-14-34-4W5	1981.2-1985.4
01-22-34-4W5	1986.6-2001.8
11-22-34-4W5	1996.3-2001.2
01-23-34-4W5	1966.5-1968.9
11-23-34-4W5	1970.4-1974.1
01-27-34-4W5	1979.3-1983.5
11-27-34-4W5	2019.8-2024.3
01-28-34-4W5	2030.0-2038.2
11-28-34-4W5	2055.8-2063.8
11-32-34-4W5	2061.9-2071.3
01-33-34-4W5	2025.3-2033.2
11-04-35-4W5	2032.9-2042.1
11-05-35-4W5	2107.3-2113.4
01-07-35-4W5	2116.5-2129.3
11-18-35-4W5	2116.7-2128.6
11-13-35-5W5	2154.9-2165.3
11-26-35-5W5	2125.9-2138.7
11-27-35-5W5	2154.9-2165.6
11-34-35-5W5	2132.0-2138.1
10-04-36-5W5	2090.8-2098.4
10-08-36-5W5	2108.2-2116.7
04-17-36-5W5	2124.4-2136.5
02-18-36-5W5	2142.6-2153.9
10-24-36-6W5	2167.0-2174.0

Garrington (con't)

12-24-36-6W5	2189.7-2200.6 m
12-26-36-6W5	2208.8-2225.2
02-34-36-6W5	2215.8-2231.0
02-35-36-6W5	2183.8-2199.0
04-35-36-6W5	2204.6-2214.3
02-03-37-6W5	2176.2-2192.9
04-03-37-6W5	2183.8-2199.0
10-17-37-6W5	2222.0-2235.6

Lochend

08-19-26-2W5	2082.3-2093.8
16-03-27-3W5	2239.0-2249.0
10-11-27-3W5	2215.9-2222.6
10-05-28-3W5	2278.6-2283.1
08-07-28-3W5	2244.0-2256.4
14-08-28-3W5	2210.0-2218.1
06-09-28-3W5	2215.0-2232.0
08-17-28-3W5	2182.0-2198.4
08-18-28-3W5	2265.3-2273.0
16-35-28-4W5	2282.0-2291.0
06-13-29-4W5	2223.0-2231.6
16-16-29-4W5	2366.0-2371.0
14-05-30-4W5	2368.0-2386.0
15-23-32-6W5	2353.4-2359.4
16-06-32-5W5	2378.0-2397.0
07-03-35-8W5	2621.6-2635.3
10-11-35-8W5	2587.8-2605.9
07-28-35-8W5	2659.4-2677.7

Off-field Areas

10-24-25-2W5	1999.4-2013.1
10-31-26-1W5	1955.8-1958.9
10-28-27-2W5	2089.4-2102.2
11-34-27-2W5	2063.7-2073.5
10-01-30-3W5	2004.1-2019.3
06-13-30-3W5	1999.5-2030.0
10-20-31-1W5	1781.9-1797.1
06-06-31-2W5	1966.6-1980.6
12-19-33-5W5	2380.4-2387.7
11-15-34-4W5	2018.1-2023.0
13-22-34-6W5	2410.0-2420.0
11-19-35-4W5	2096.4-2108.6
13-08-35-6W5	2440.2-2449.1
07-01-35-7W5	2516.0-2528.0
04-21-37-6W5	2175.4-2190.6